



# Heavy Ion Physics with the ATLAS detector

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*(for the ATLAS collaboration)*

**ATLAS**

<http://atlas.ch>

Asilomar June 9-16, 2006

# My own view of heavy ion collisions



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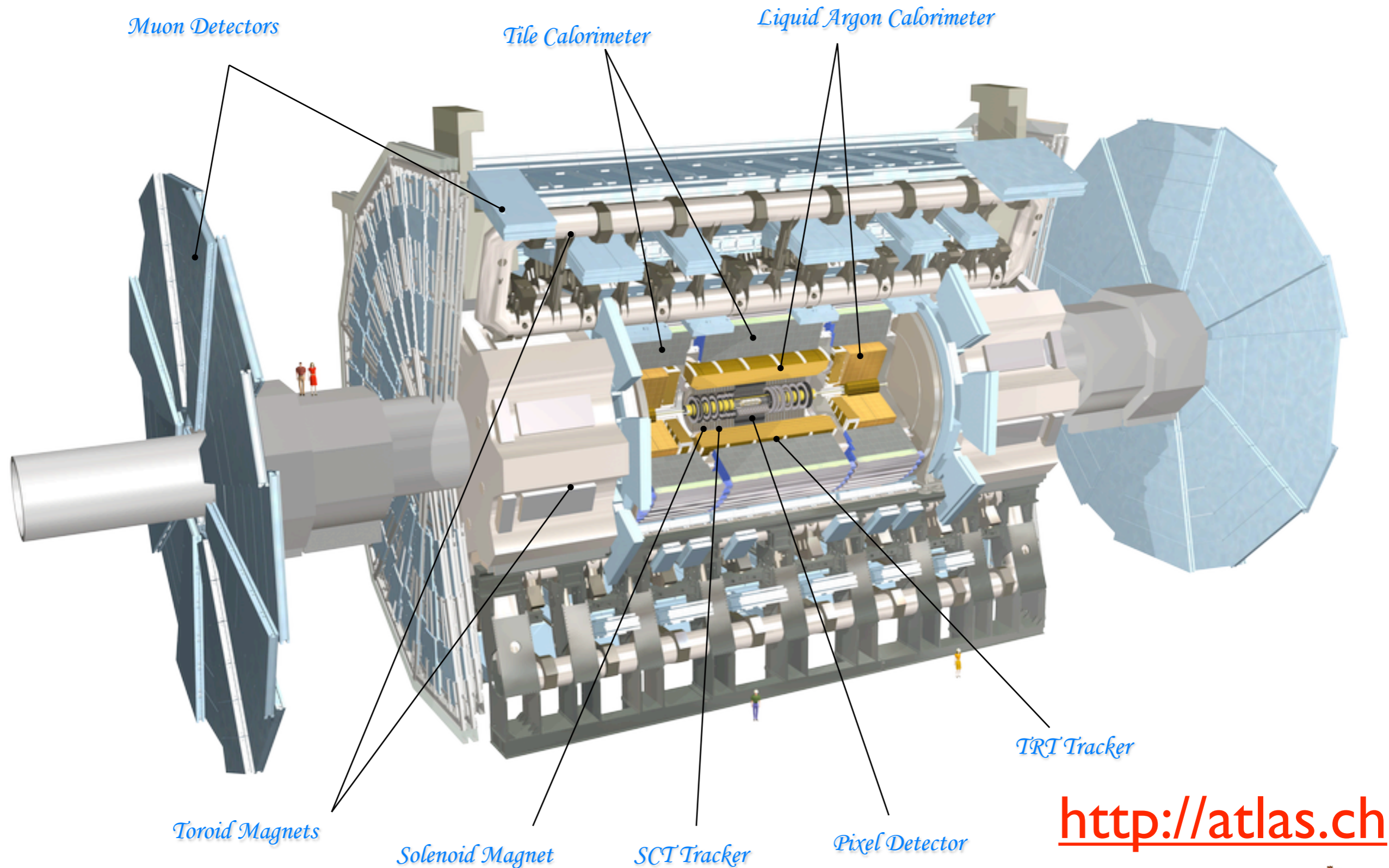
A word of caution... (in form of a quote)

*“In the beginning there was nothing and God said: Fiat Lux and light was made. There was still nothing, but you could see it a whole lot better”.*

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# What is ATLAS?



<http://atlas.ch>

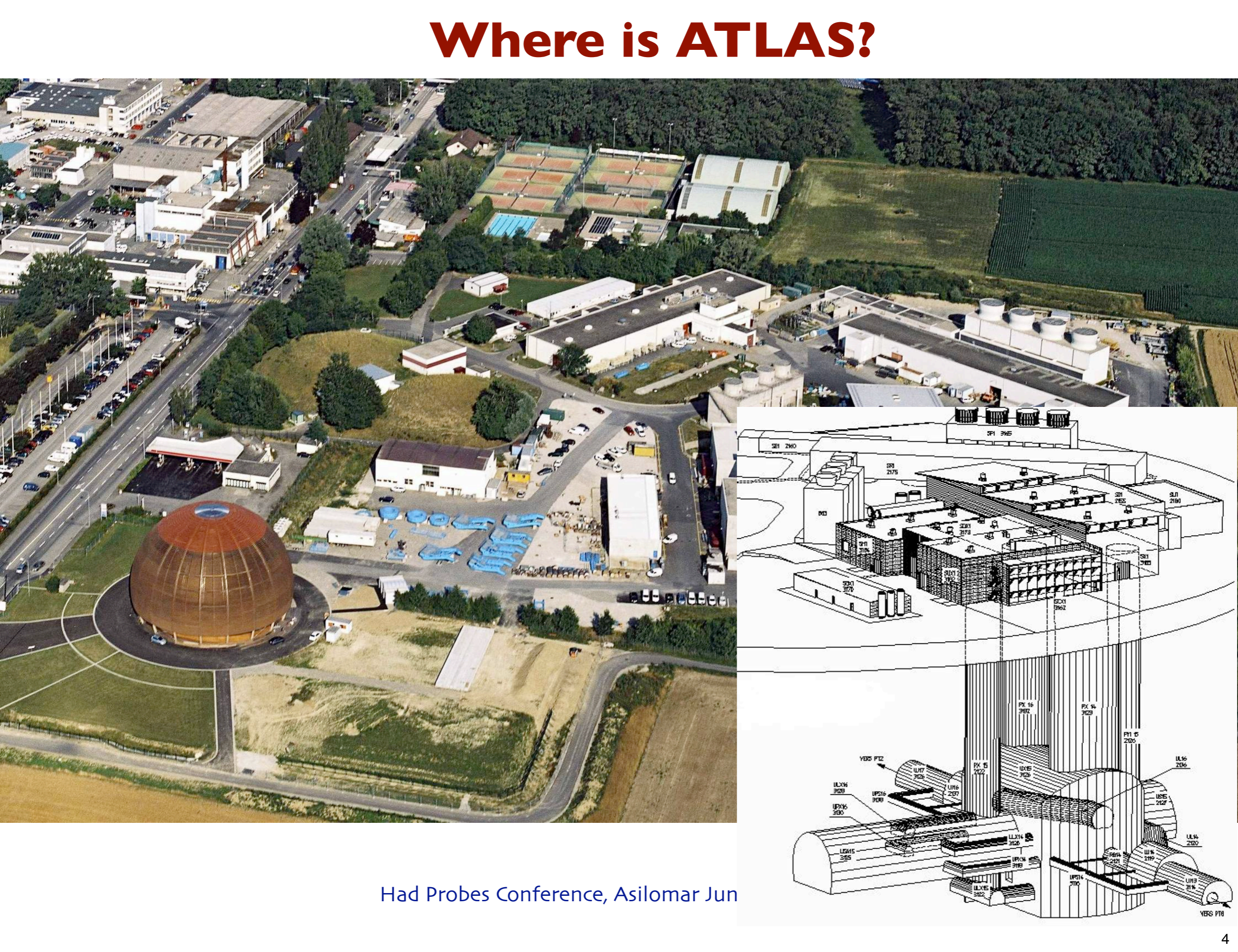
14 TeV pp collisions at  $10^{34}$  luminosity

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[illegible]

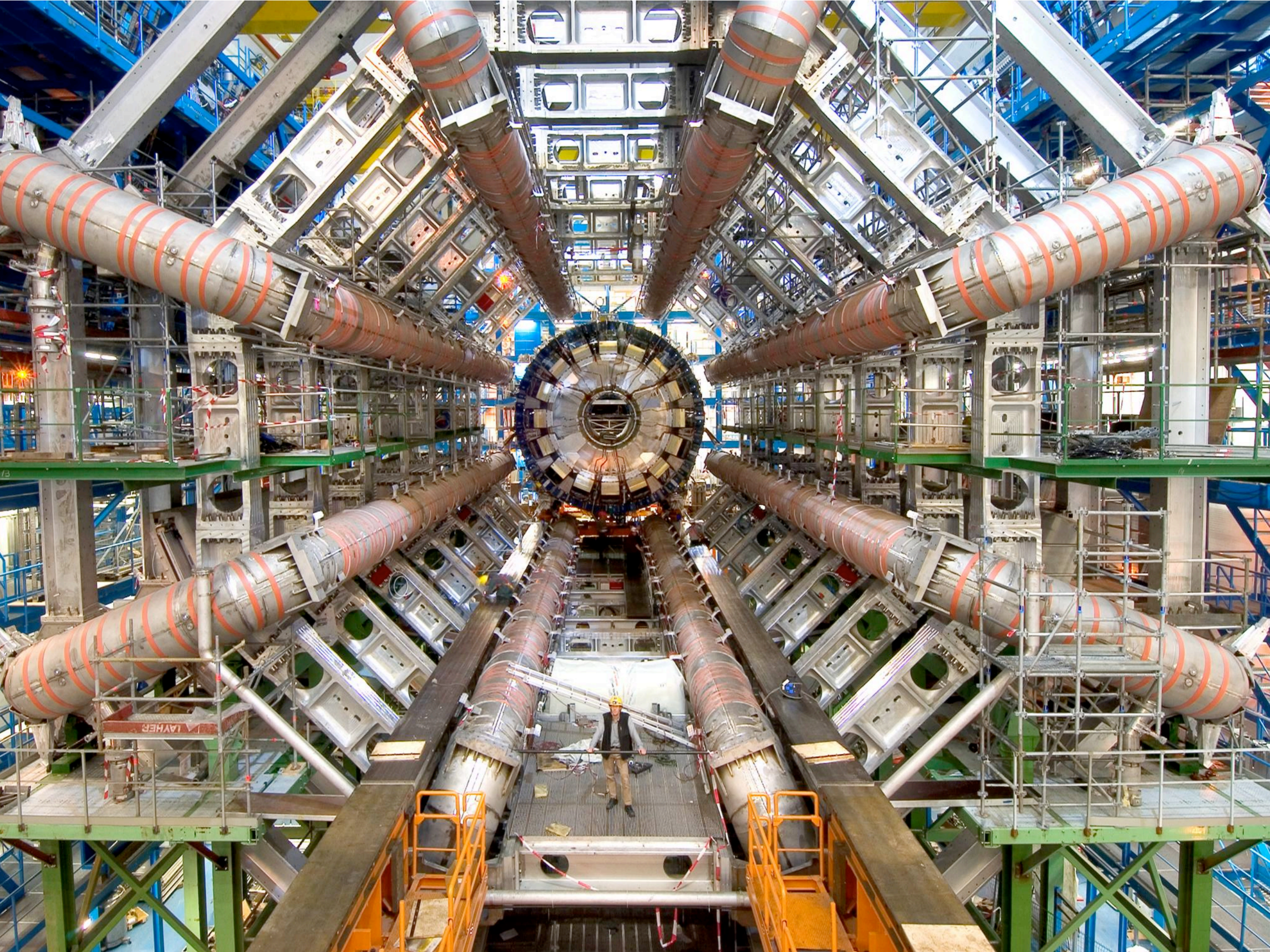
# Where is ATLAS?

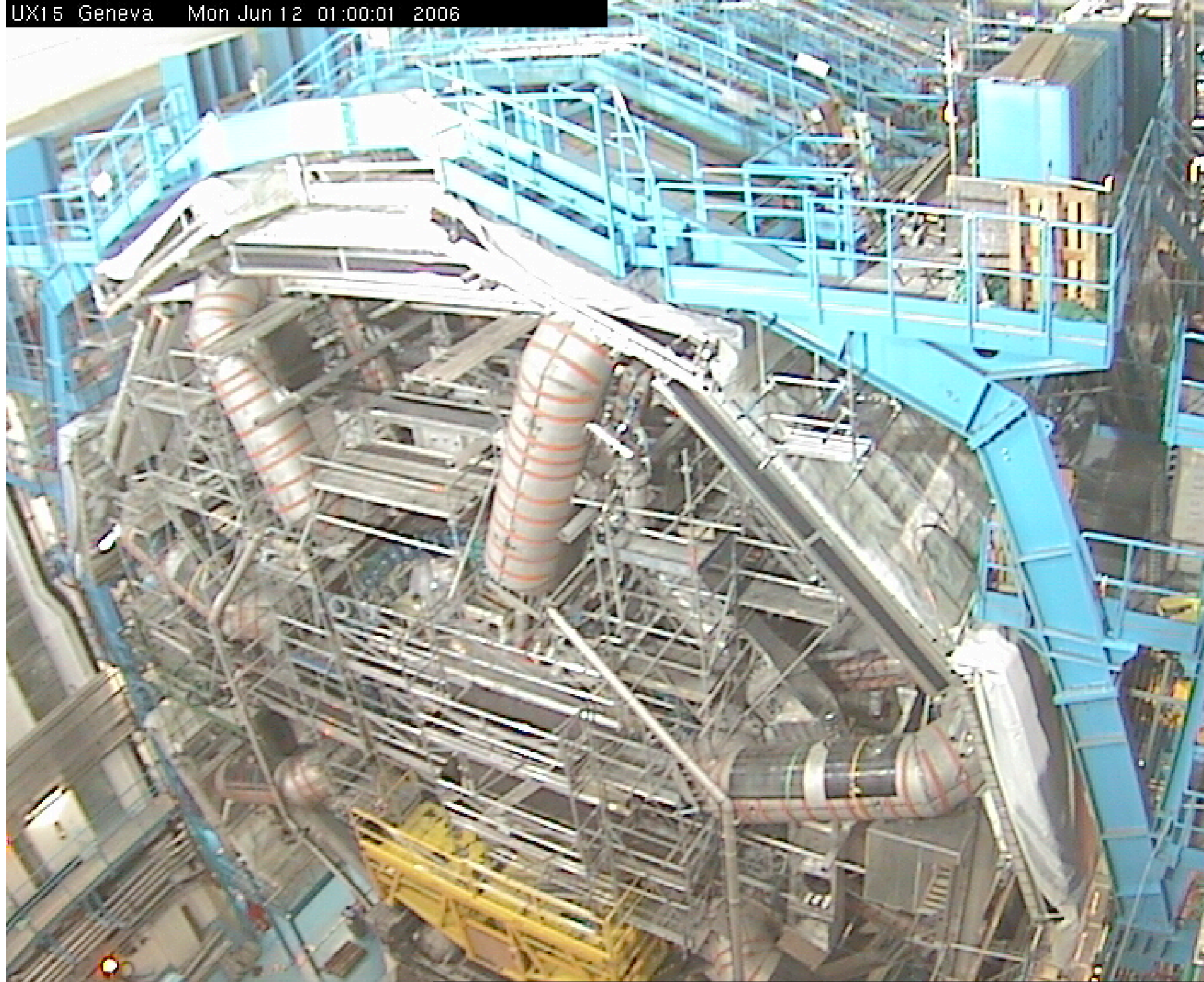


The image is a composite. The top half is an aerial photograph of the ATLAS experiment site at CERN. It shows a large, circular, brown, dome-like structure, which is the entrance to the LHC tunnel. Surrounding this are various industrial buildings, parking lots, and a road. The bottom half is a technical diagram of the ATLAS detector. It shows a cross-section of the detector with various components labeled, including the ATLAS Torus, ATLAS Barrel, ATLAS Endcap, and ATLAS Muon Chambers. The diagram is a black and white line drawing with labels in a sans-serif font.

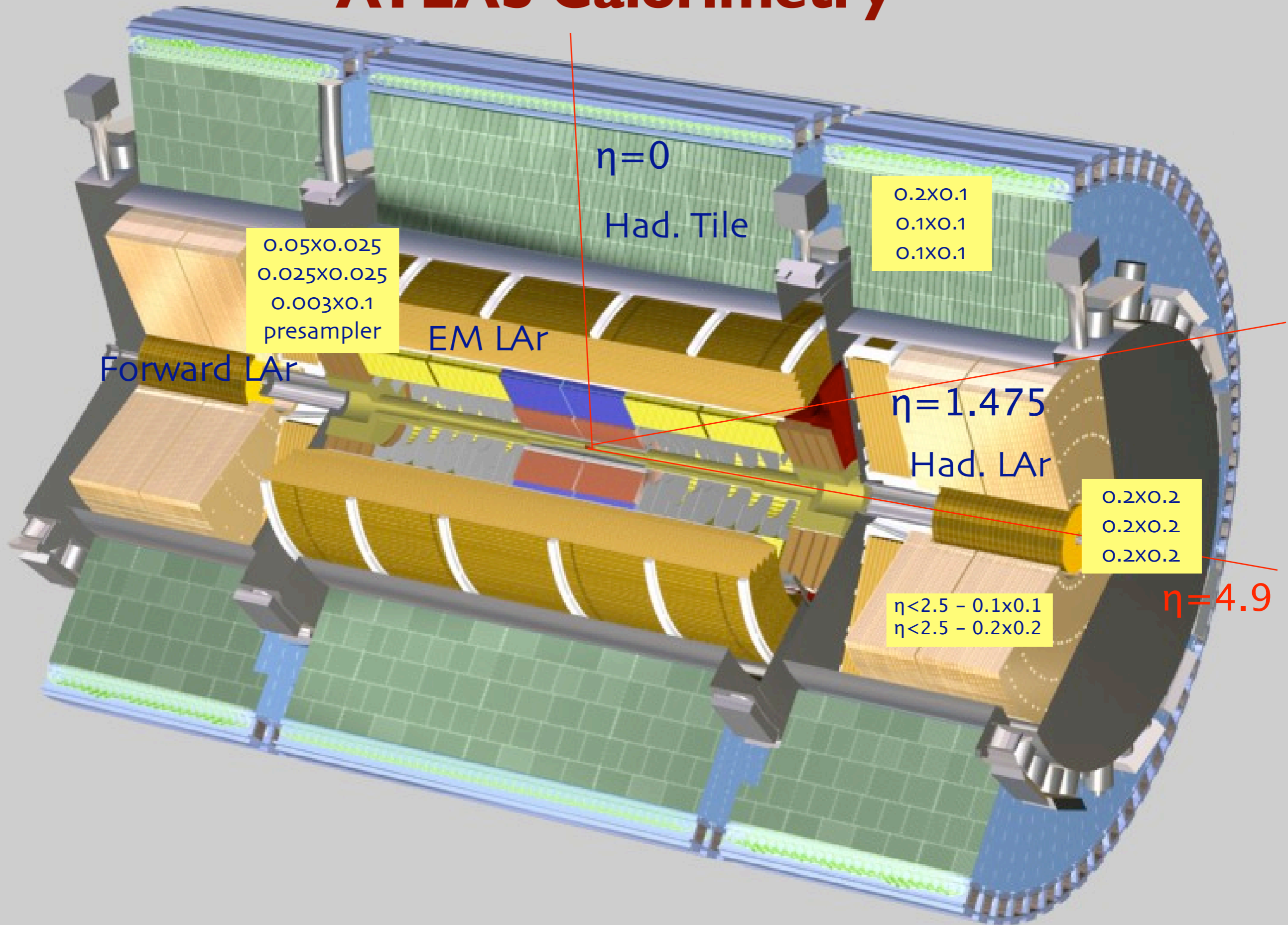
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4



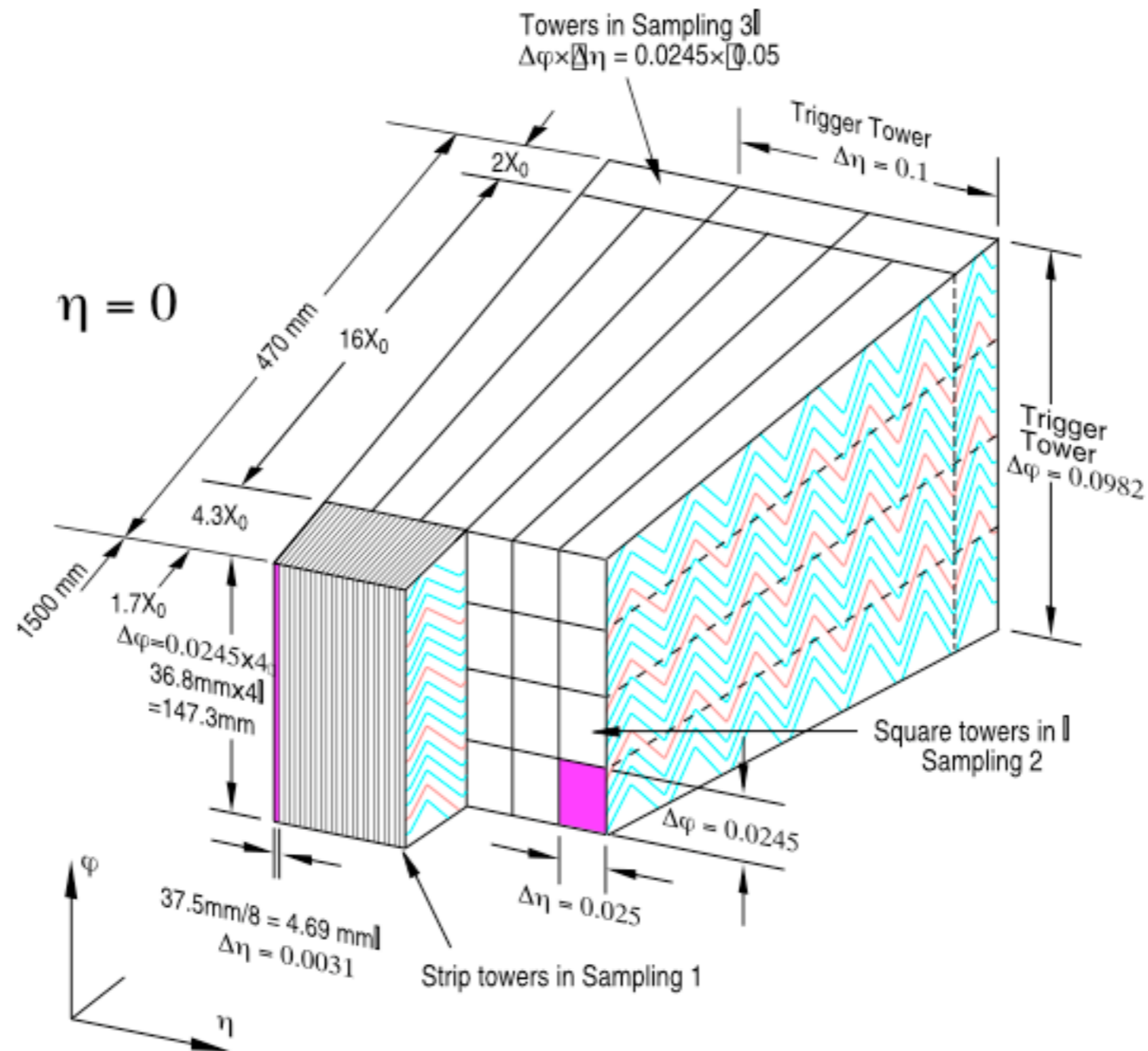


# ATLAS Calorimetry



# ATLAS Calorimetry

Segmentation, Segmentation, Segmentation...



Designed specifically for  $\gamma/\pi^0$  rejection, or clean photons

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# ATLAS Calorimetry

EM Calorimeter  
Energy Resolution

$$\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.2\%$$

Had Calorimeter  
Energy Resolution

$$\frac{\sigma_E}{E}(\pi) = \frac{47\%}{\sqrt{E}} \oplus 2\%$$

Single Particle Angular  
Resolution

$$\sigma_\theta = \frac{60 \text{ mrad}}{\sqrt{E}}$$

EM Calorimeter timing  
resolution

$$\sigma_\tau = \frac{4.15}{E} \text{ ns.GeV}$$

Intrinsic Jet energy  
resolution

$$\frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E}} \oplus 2\%$$

# Jets in 3D!

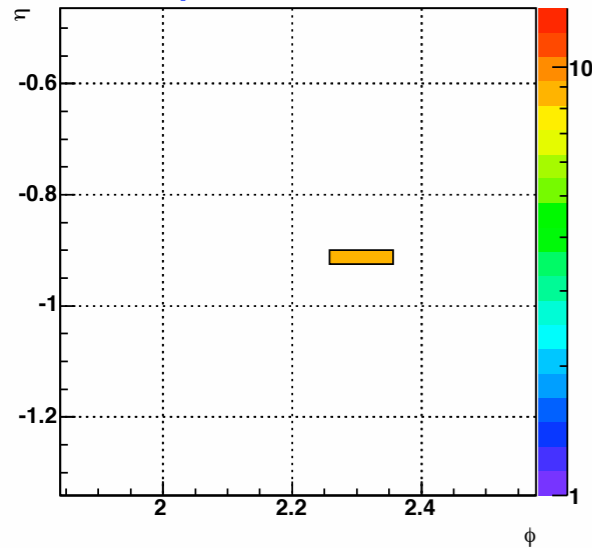
(and in color)

$E_T = 100$  GeV (jet only)

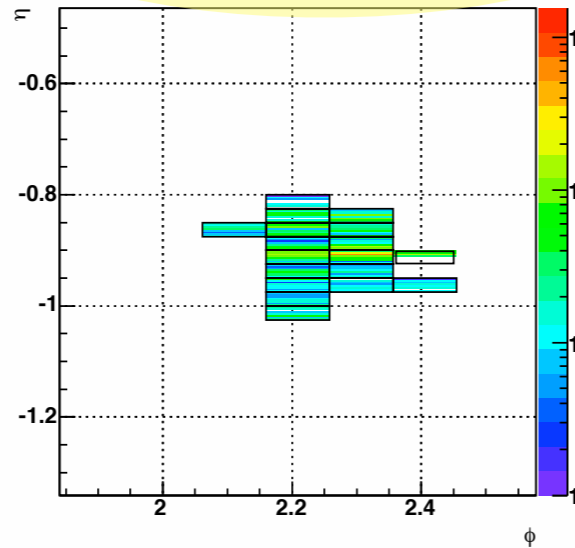
$\Delta\eta \times \Delta\phi = 0.8 \times 0.8$

**Contains 60% of soft background energy!**

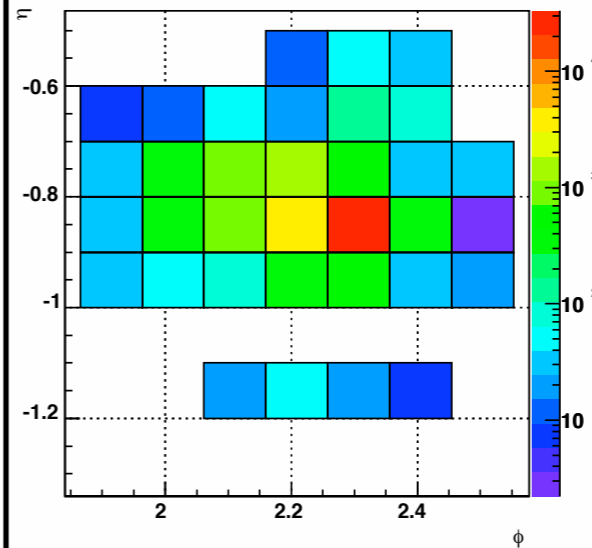
Presampler



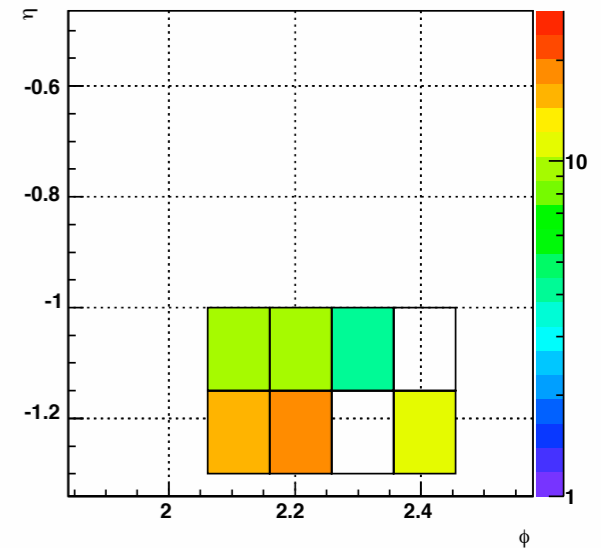
ECAL Front



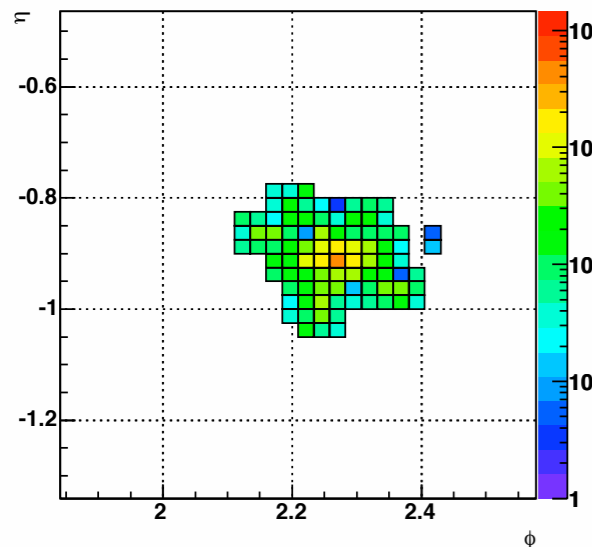
Tile 1



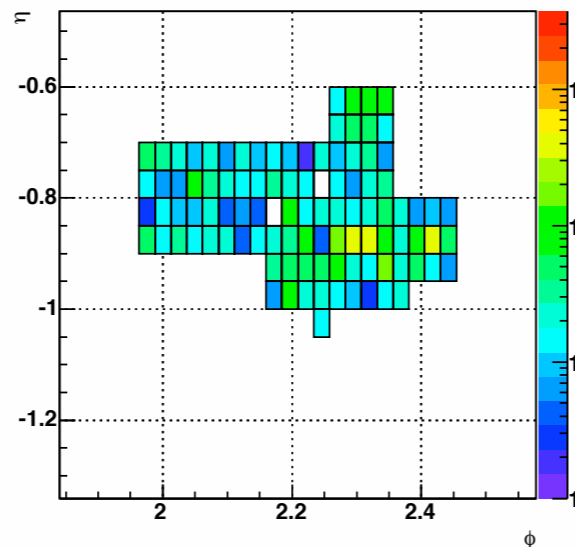
Scintillator



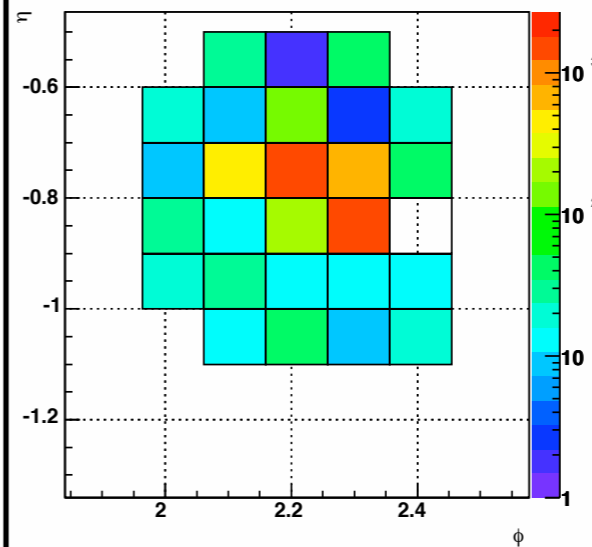
ECAL Middle



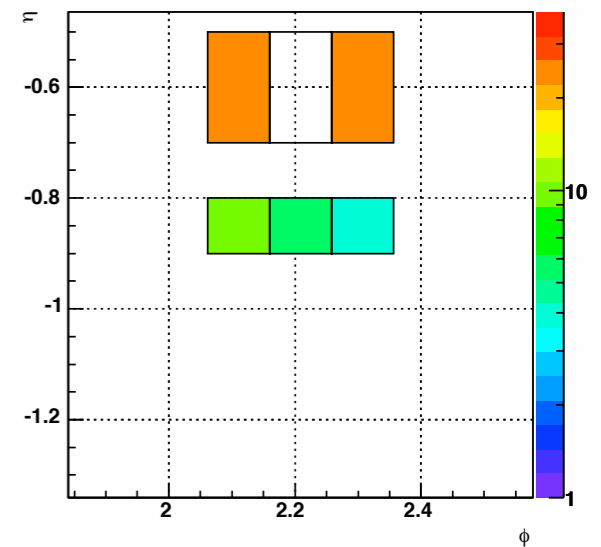
ECAL Back



Tile 2



Tile 3



*EM Calorimeter*

*Hadronic Calorimeter*

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# Jets in 3D!

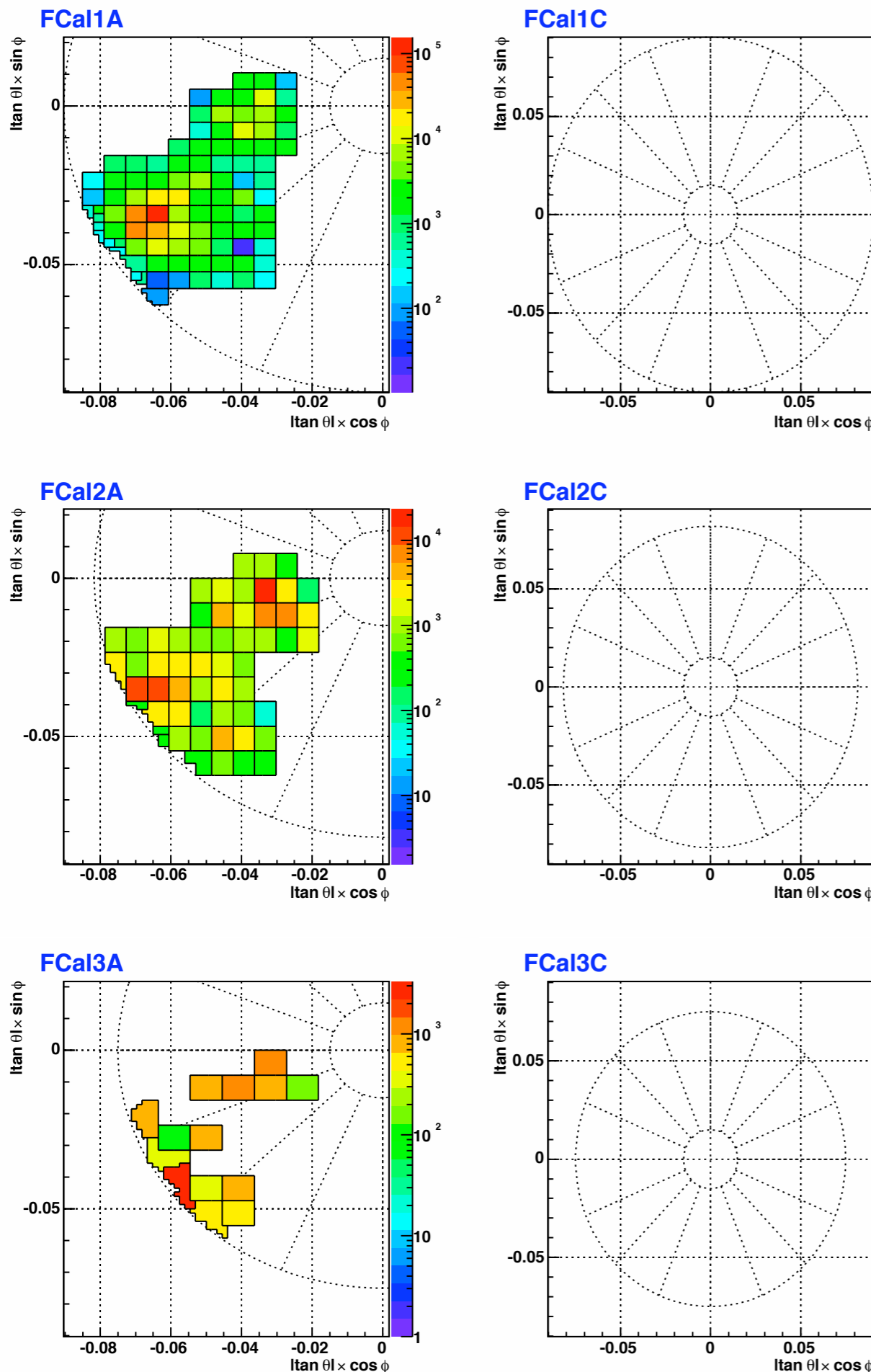
(Forward Calorimeter-only)

100 GeV (ET) jet in forward calorimeter. ( $\sim 3.0 < \eta < 4.9$ )

Important for pA physics down to  $x \sim 10^{-5}$

Performance in AA needs to be evaluated but expect jets  $\sim 50$  GeV.

Isolated photons?



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# Tracking

ATLAS performs tracking for  $|\eta| < 2.5$ .

The muon spectrometer is stand alone and outside of the calorimeter volume. The inner detector has three components:

- Pixel Detector (Pixel)

- Silicon Tracker (SCT)

- Transition Radiation Tracker (TRT)

Momentum resolution for muon spectrometer stand alone is  $\sim 2.5\%$  for up to  $p_T \sim 200$  GeV for  $|\eta| > 1.5$ , and  $\sim 1.5\%$  for the inner detector.

Tracking momentum resolution is  $\sim 2.5\%$  up to  $p_T \sim 100$  GeV for  $|\eta| > 1.5$  for both muon stand alone and tracker.



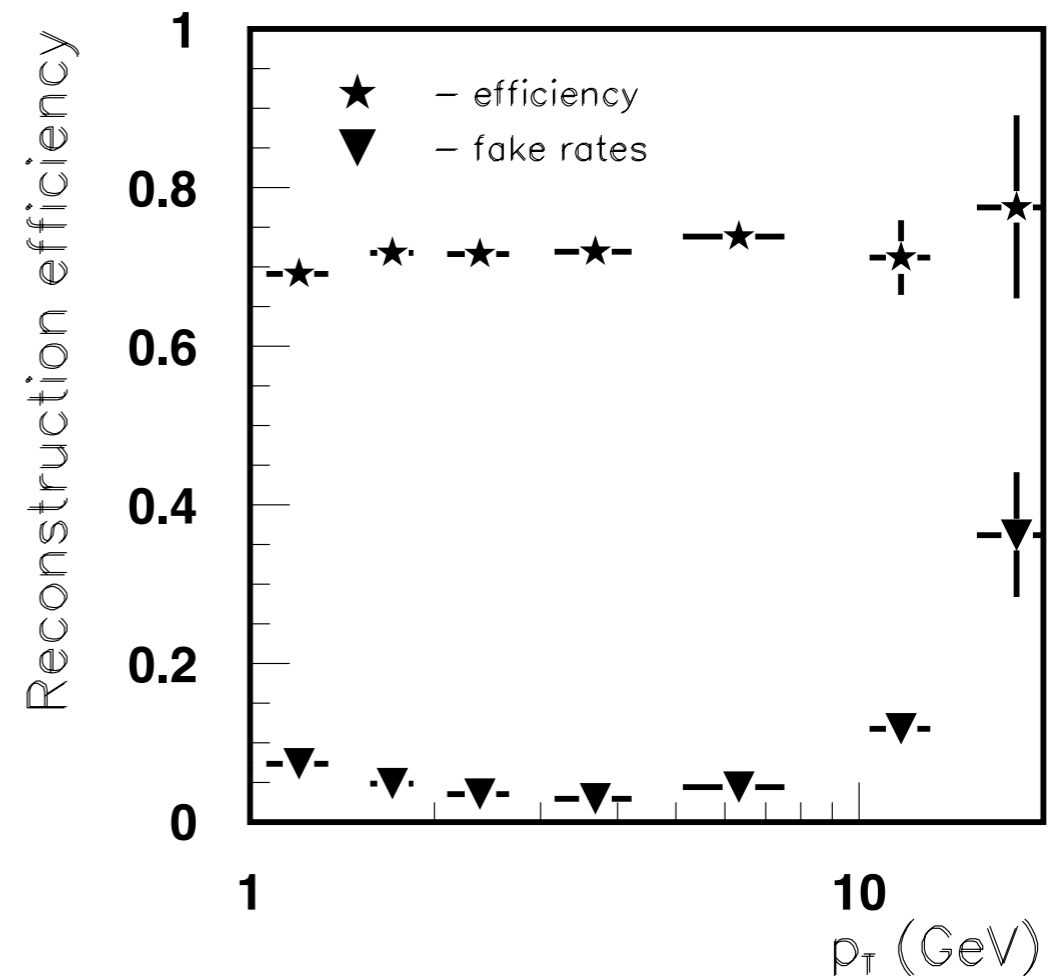
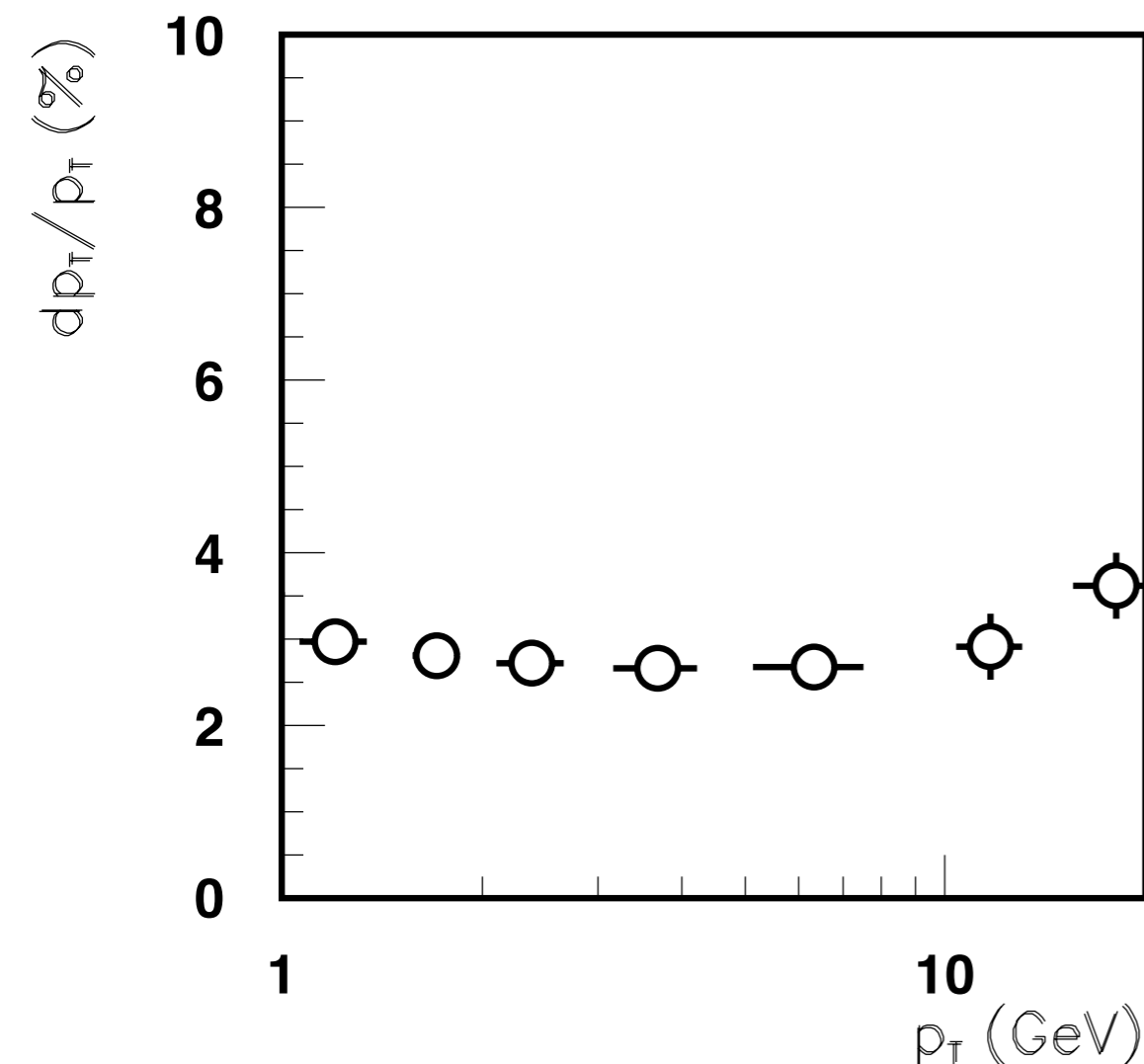
# H.I. Tracking

Standard ATLAS reconstruction for pp

Uses Pixel and SCT, not TRT

$p_T$  threshold is 0.5 GeV

Uses 10 hits out of 11 available



For  $p_T \sim 1 - 10$  GeV  $\epsilon = 70\%$ , fake  $\sim 5\%$

Momentum resolution is  $\sim 3\%$   
(2% in barrel and 4-5% in end caps)

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# Forward Detectors

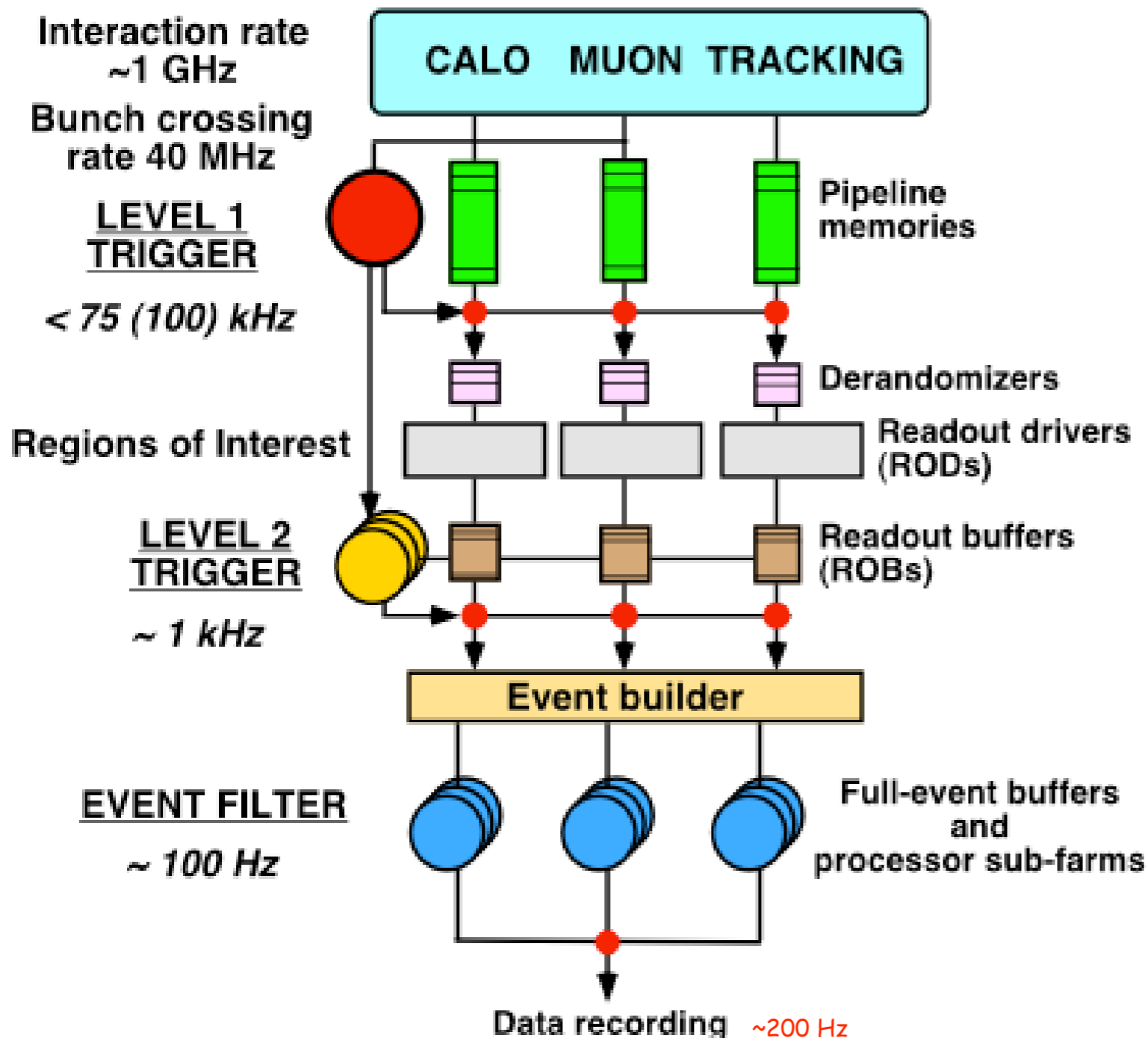
**LHCf** - Is an effort by Japanese astrophysics groups. Not expected to survive full pp luminosity.

**ZDC** - Zero degree calorimeter is now a joint effort led by BNL and Yale HEP.

**LUCID** - similar to CDF. Will monitor luminosity but can be used to measure particle multiplicity in  $6 < \eta < 7$ .

**Roman Pots** - Located 420m away from the interaction point. Mostly for diffractive physics in pp.

# Trigger and DAQ



For Pb-Pb collisions the interaction rate is 8 kHz, a factor of 10 smaller than LVL1 bandwidth (100 kHz).

Further reduction by requiring central collisions in FCAL, high  $p_T$  jets, di-muons, or pre-scaled minimum bias events (possible in FCAL).

The event size for a central collision is  $\sim 5$  Mbytes. Similar bandwidth to storage as pp implies  $\sim 50$  Hz data recording.

# Trigger and DAQ

Triggering on events with  $b < 10$  fm - uses full ATLAS Calorimetry

High Level Triggers (ATLAS T/DAQ) - jet trigger, di-muon trigger,...

Jet rate  $\sim 40$  Hz for  $E_T$  threshold = 50 GeV

$\sim 0.1$  Hz for  $E_T$  threshold = 100 GeV

## Selection signatures

LVL1 signature	HLT signature	Physics coverage
random	random	Zero-bias sample
INT(FCAL)	int(FCAL)	Centrality/interaction
EM	e	$Z \rightarrow ee$
EM	$\gamma$	Photon production
2EM	2e	$Z \rightarrow ee$
MU	$\mu$	$Z \rightarrow \mu\mu, \gamma \rightarrow \mu\mu$
2MU	2 $\mu$	$Z \rightarrow \mu\mu, \gamma \rightarrow \mu\mu$
nJ	nj	Jet production

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# Software and Computing

ATLAS Heavy Ion physics have evolved into the ATLAS software framework - it was a somewhat painful process, but it is now done!

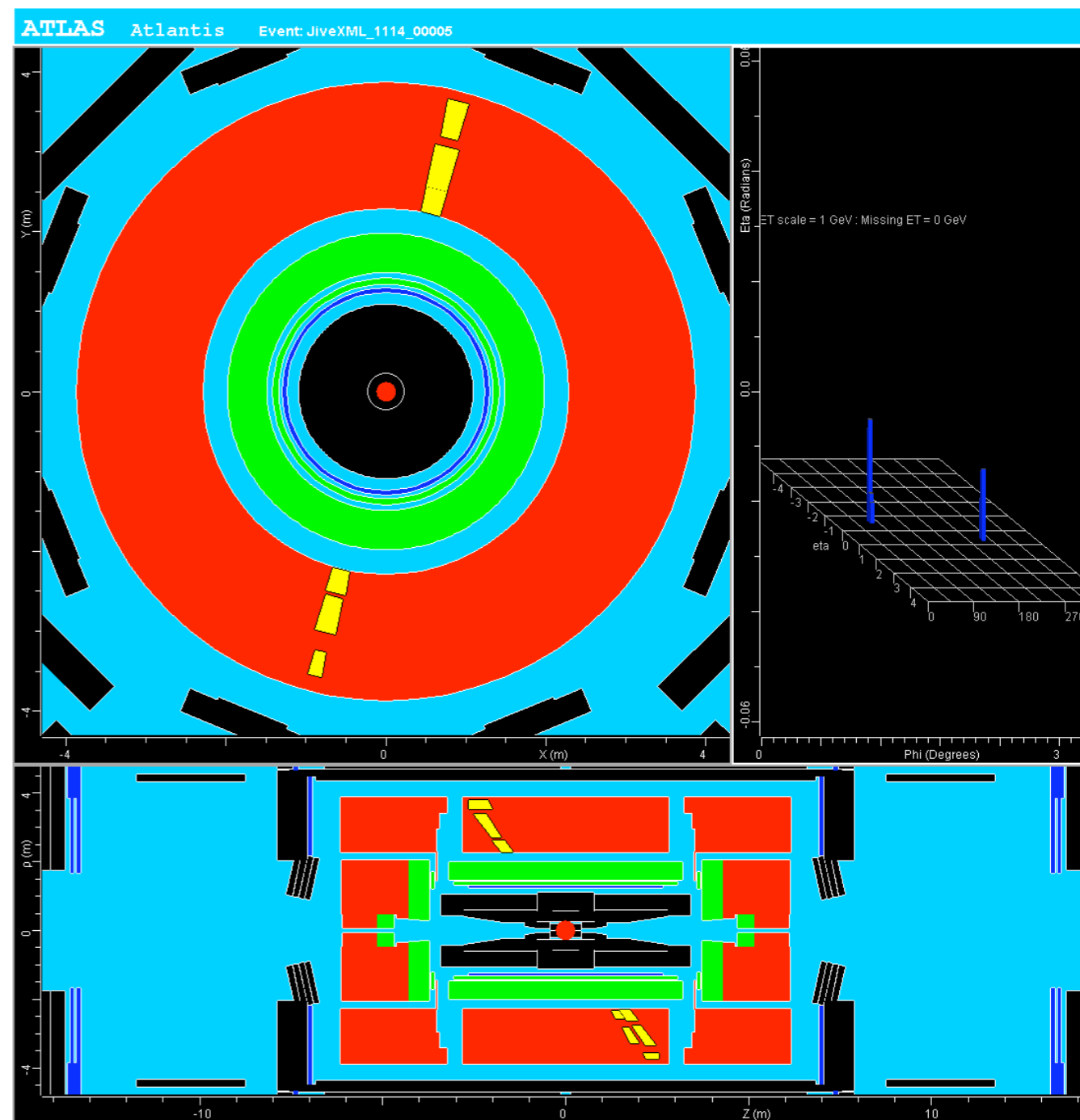
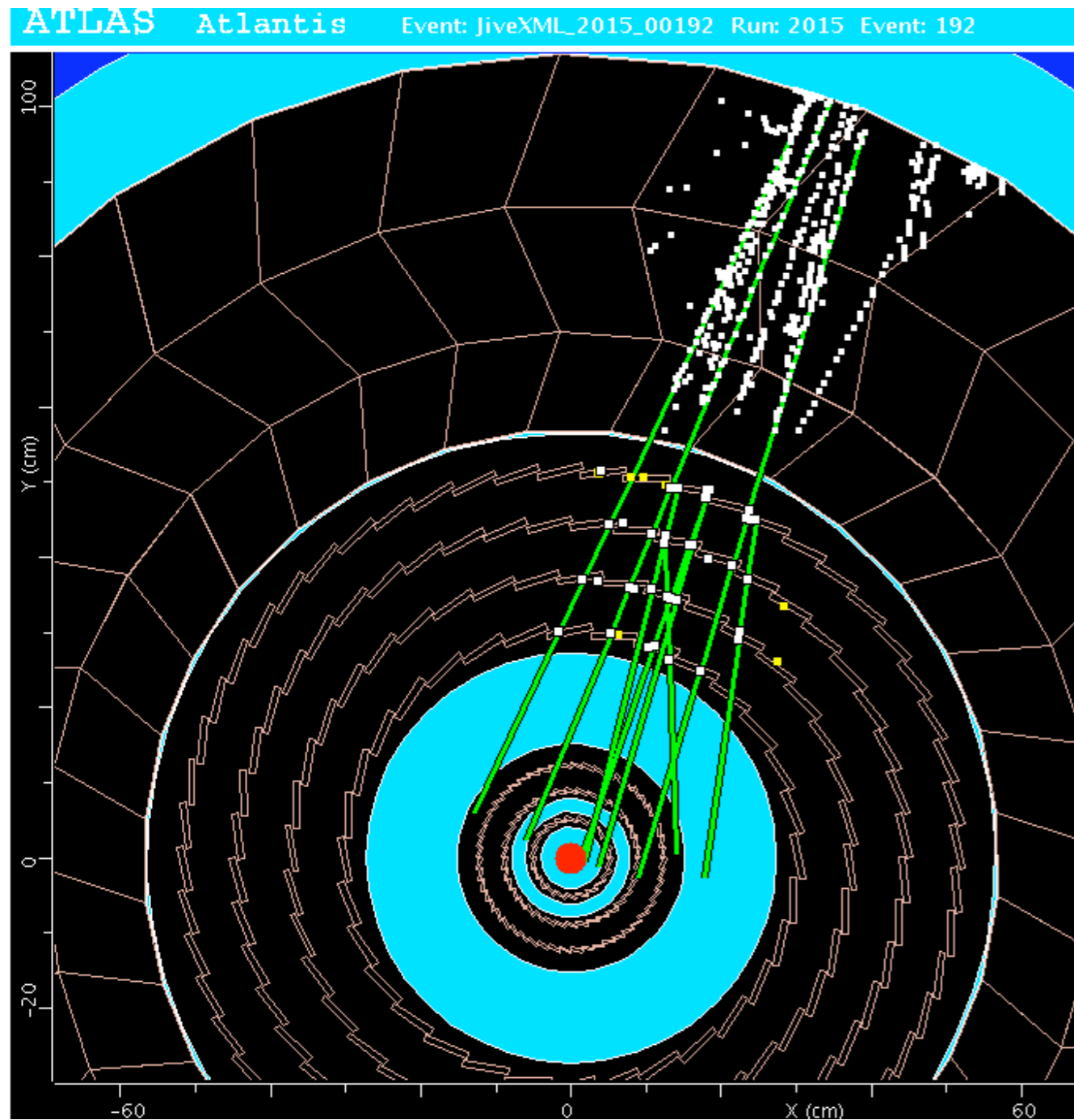
Simulations are now possible to be submitted as part of ATLAS simulation effort through GRID computing.

We are now starting to contribute to ATLAS software development, e.g. development of new jet finding software, and service packages.

In the US, heavy ion data will be hosted by BNL Tier 1 computing site.



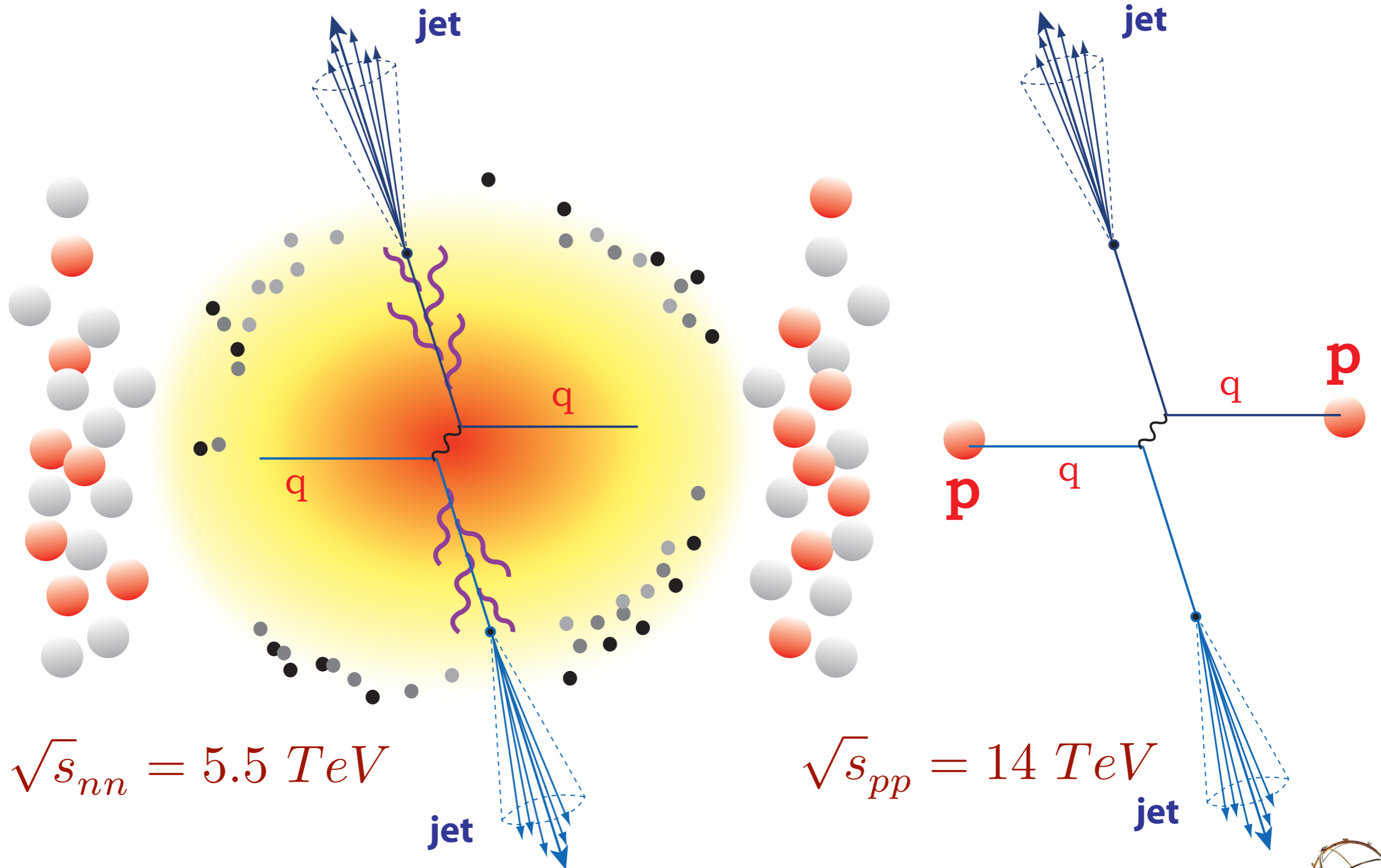
# A Real ATLAS Event!



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# QGP and Calibrated Probes



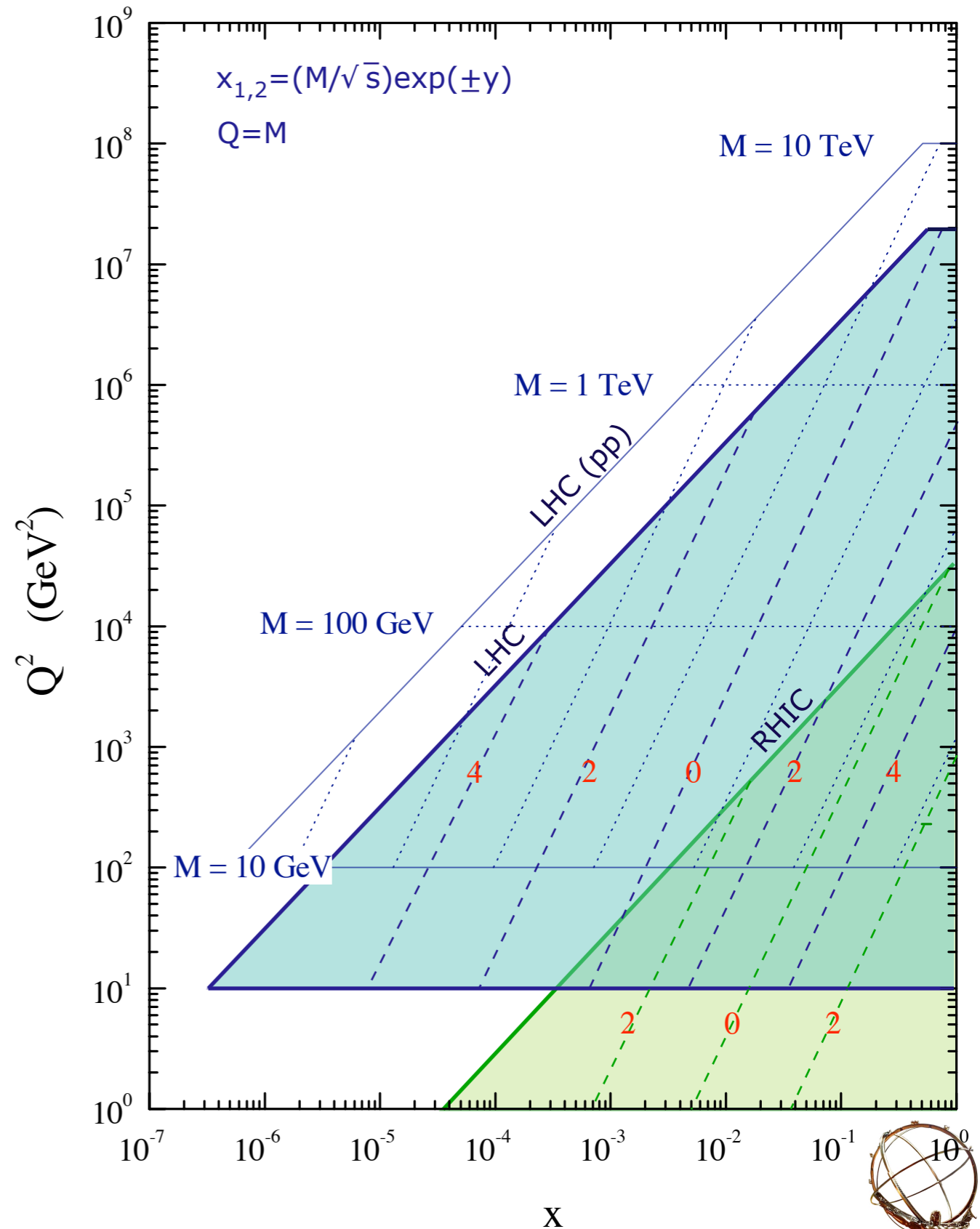
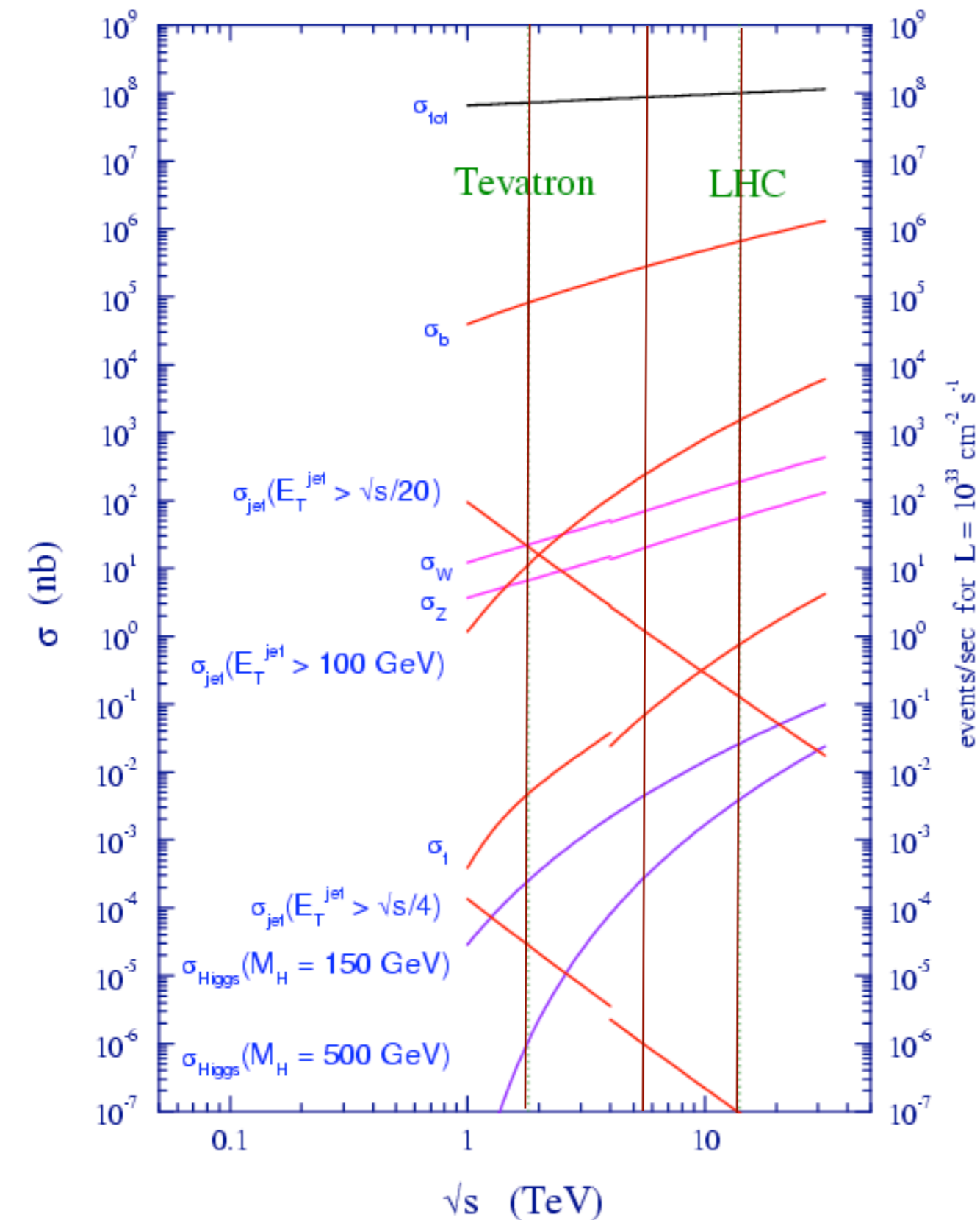
$$\sqrt{s_{nn}} = 5.5 \text{ TeV}$$

$$\sqrt{s_{pp}} = 14 \text{ TeV}$$

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# Probes, Probes, Probes



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# Rates in the ATLAS acceptance

pp@ $10^{33}\text{cm}^{-2}\text{s}^{-1}$

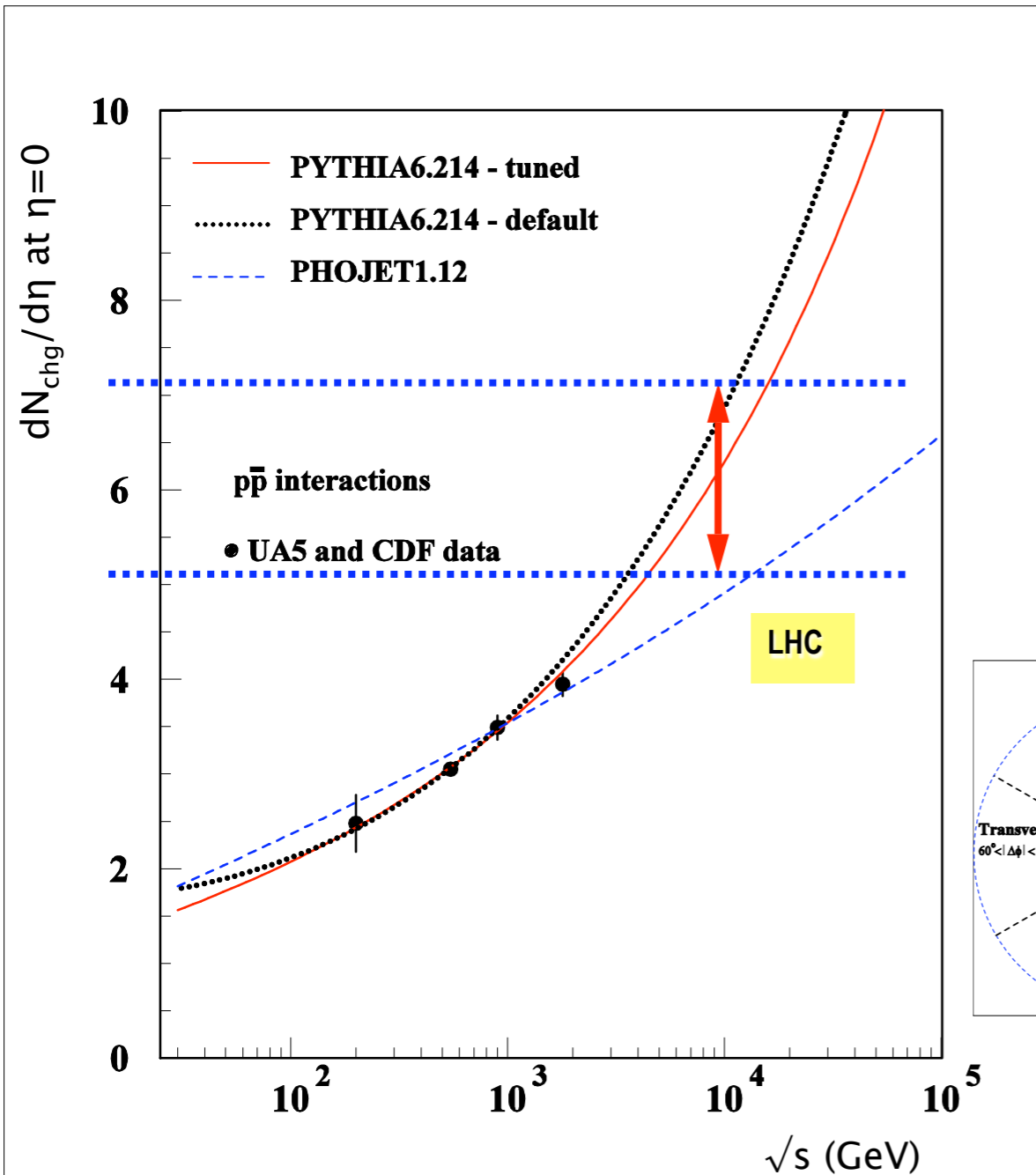
PbPb@ $4\times 10^{26}\text{cm}^{-2}\text{s}^{-1}$

Process	ev.s <sup>-1</sup>	10 fb <sup>-1</sup>	ev.s <sup>-1</sup>	month
$W^{\pm} \rightarrow e\nu$	15	$10^8$	$3\times 10^{-3}$	3000
$Z \rightarrow e^+e^-$	1.5	$10^7$	$5\times 10^{-4}$	500
$t\bar{t}$	1	$10^7$	$4\times 10^{-5}$	40
$b\bar{b}$	$5\times 10^5$	$10^{12}$	30	$3\times 10^7$
Higgs(150 GeV)	0.02	$10^5$	$2\times 10^{-6}$	2
$\tilde{g}\tilde{g}$	0.001	$10^4$	$1\times 10^{-7}$	0.1
Black Holes	0.0001	$10^3$	$3\times 10^{-8}$	0.02
$j > 100\text{ GeV}$	$10^3$	$10^{10}$	1.5	$1.5\times 10^6$
$\gamma + j(>50\text{ GeV})$			1	$1\times 10^6$

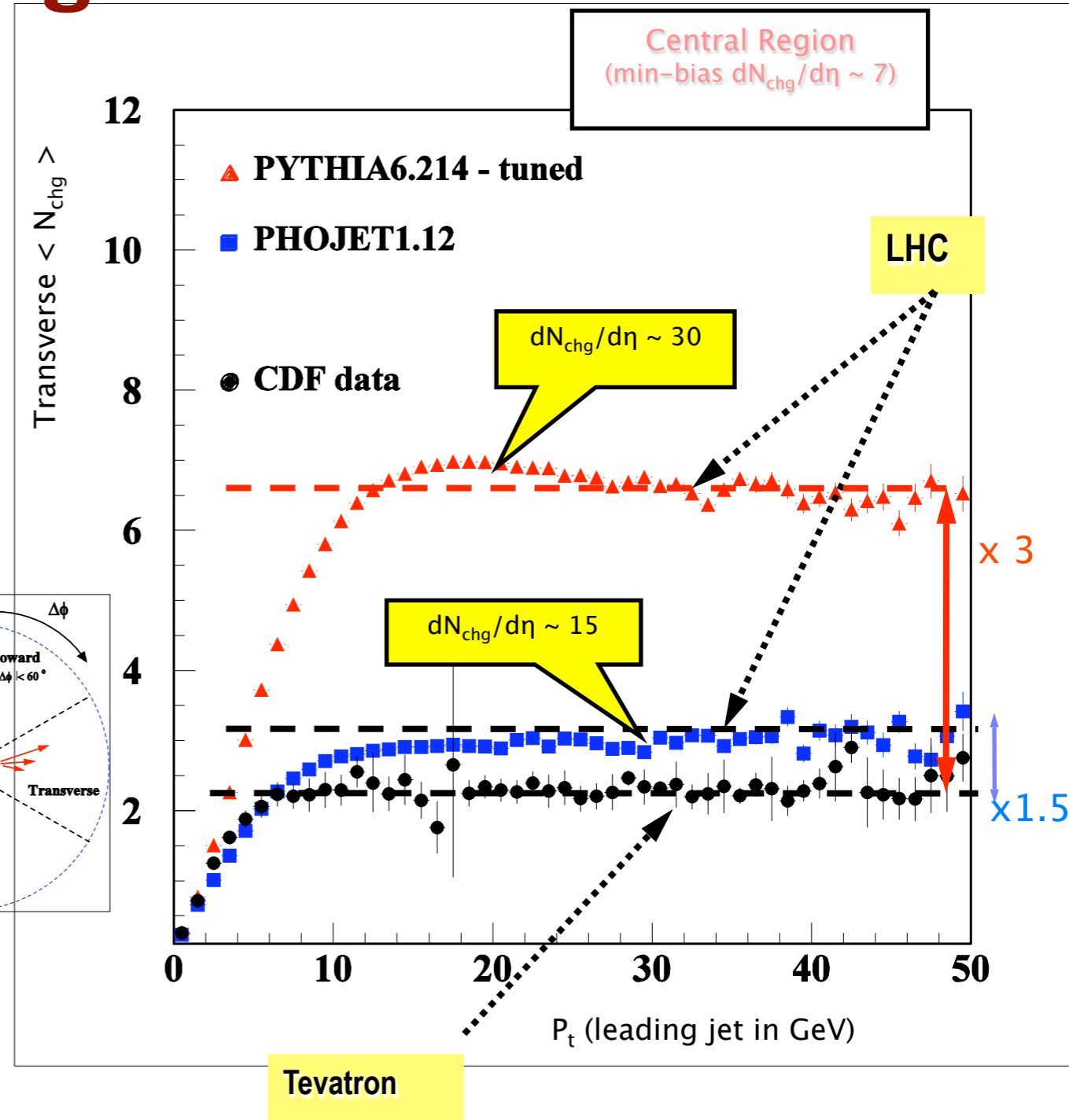
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# Understanding the basics



## Particle multiplicity



## Underlying Event

A *minimum bias group*, a joint effort between the heavy ion and Standard Model groups, has been recently created in ATLAS.

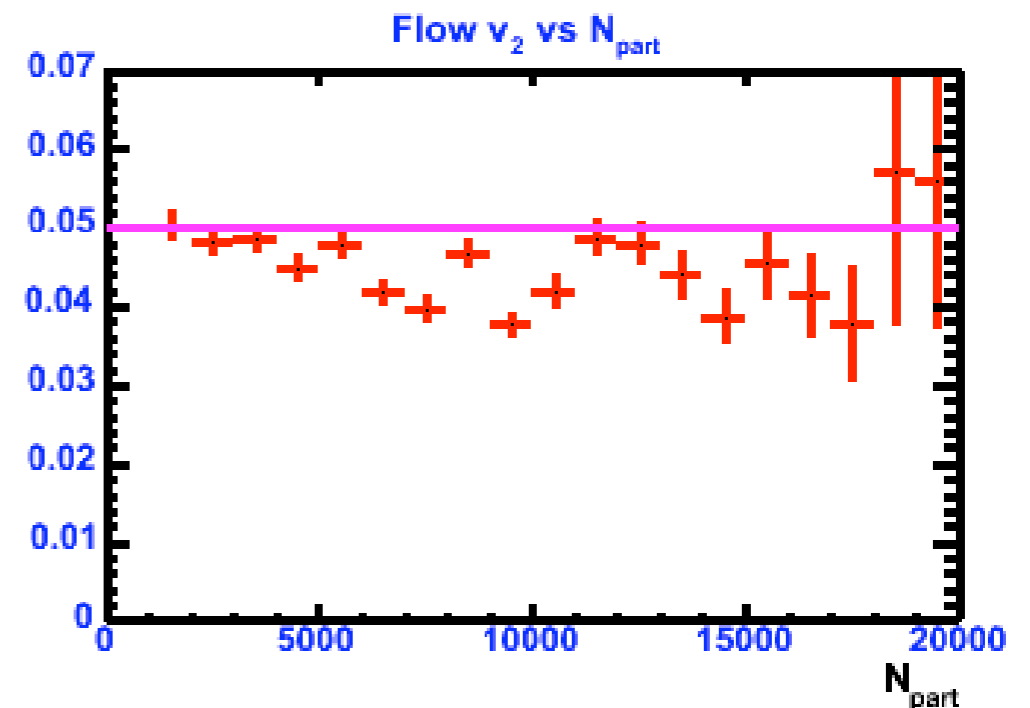
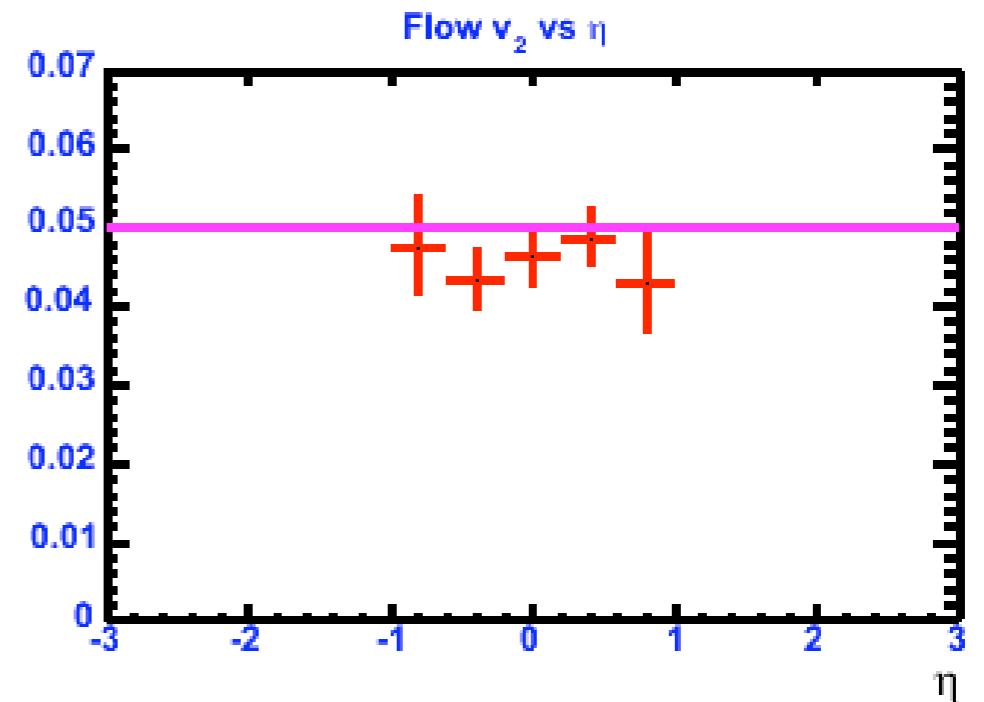
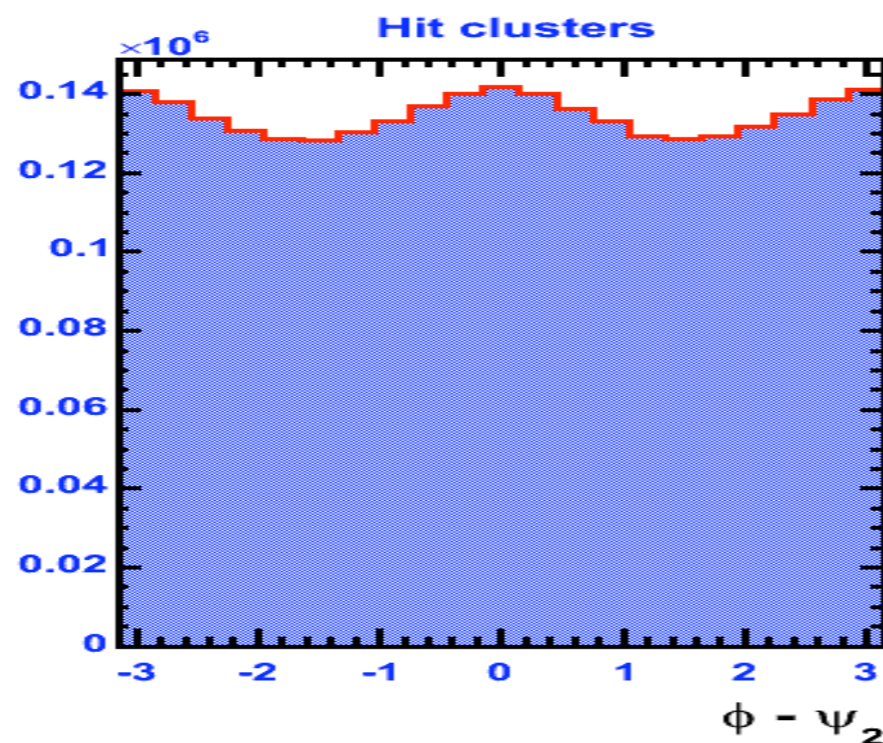
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# Elliptic Flow

$v_2$  measurable using Pixel (barrel) and Forward Calorimeter  
(reaction plane reconstruction)

Generation of HIJING events with flow with  
 $v_2 = 0.05$ ;  $\text{const}(N_{\text{ch}}, \eta, y, p_T)$  by modification  
of azimuthal angle  $\phi$



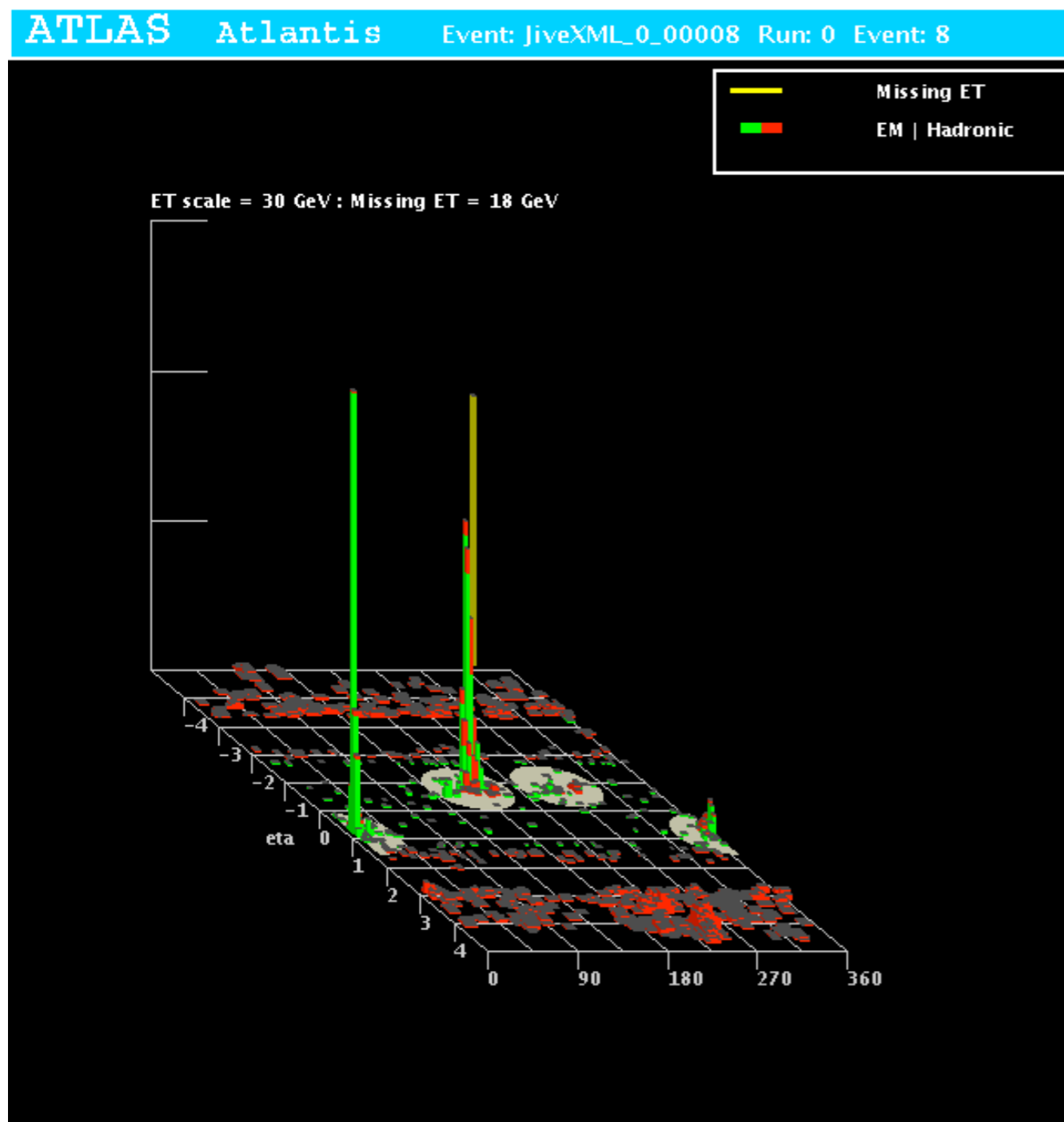
Reconstruction:

~10% is due to non-flow correl and will be accounted for by MC correction

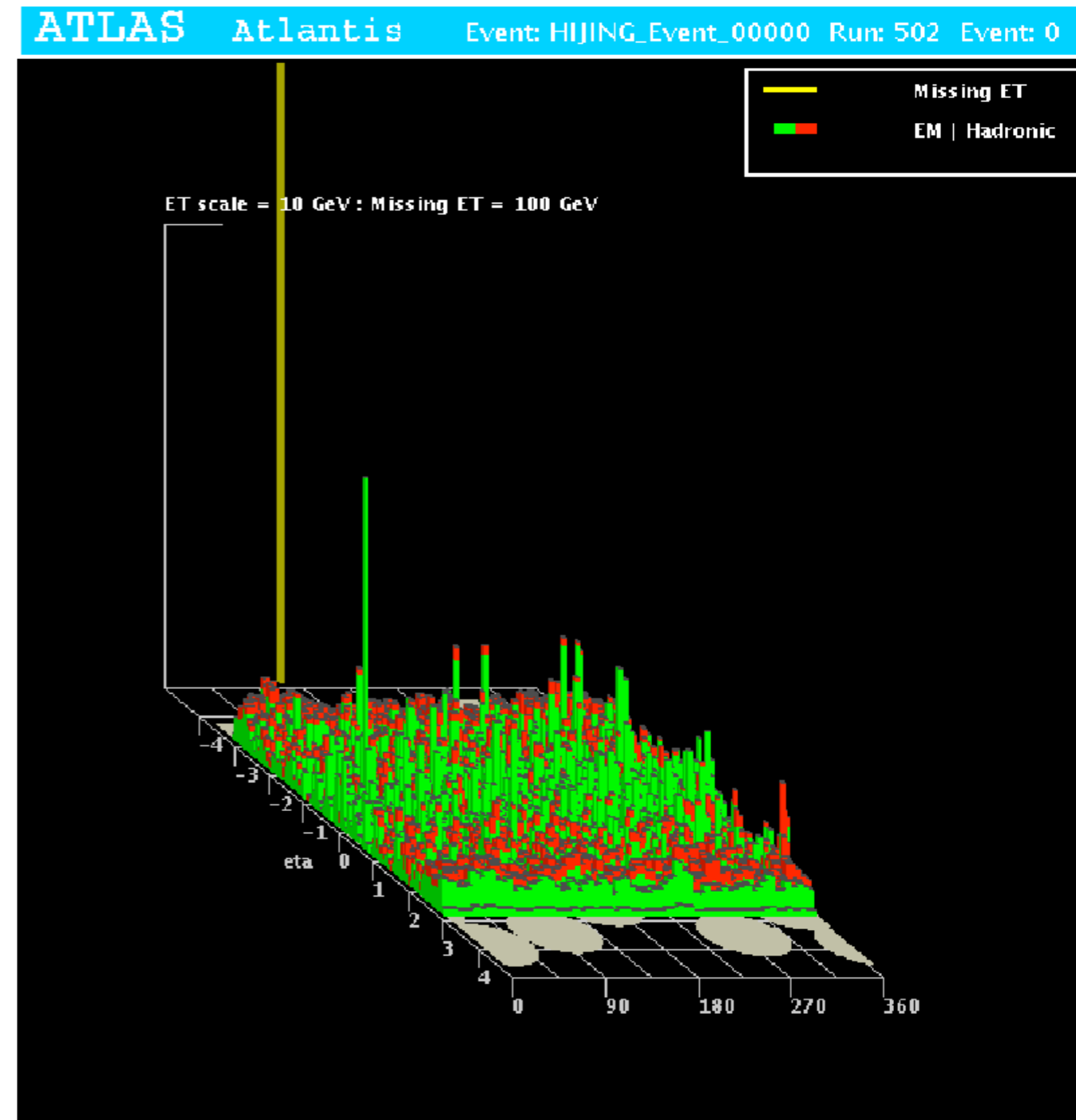
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# Jets in Heavy Ion



Pythia Jet



Pythia Jet and Hijing underlying event

*$\sim 2\text{GeV}$  in  $0.1 \times 0.1$  EM tower, or  $\sim 0.75$  GeV for electron signal*

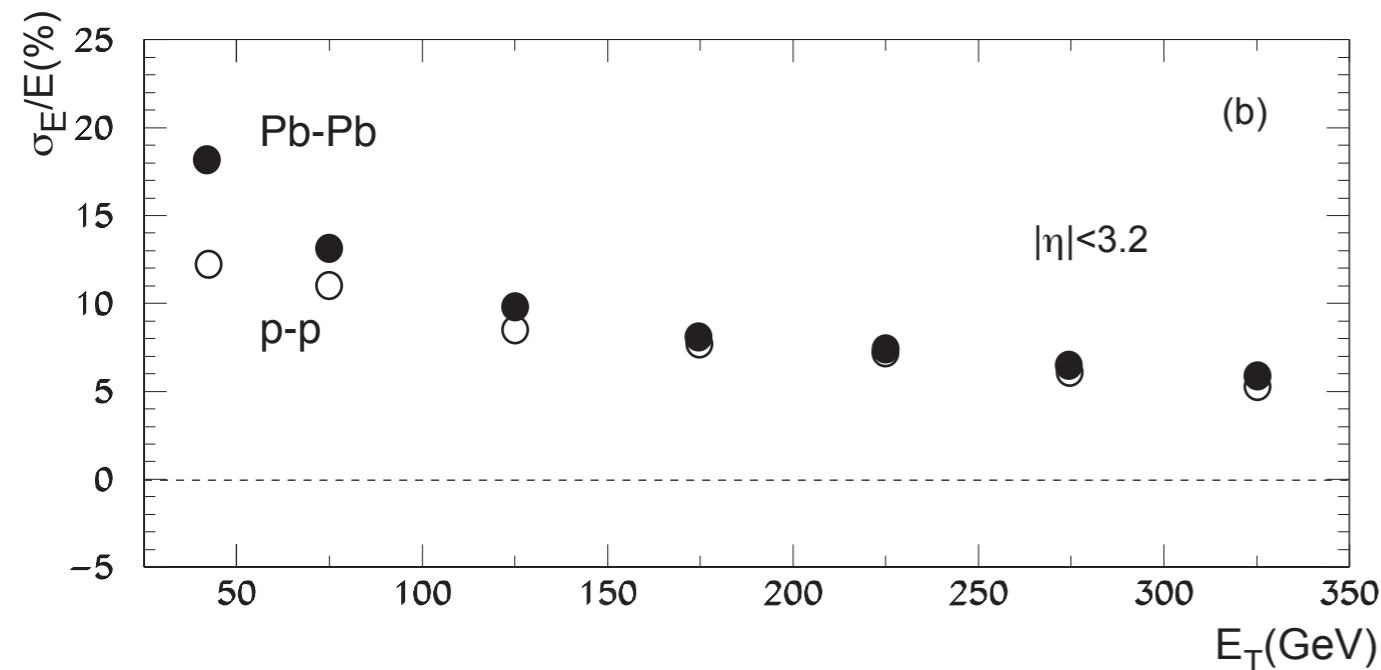
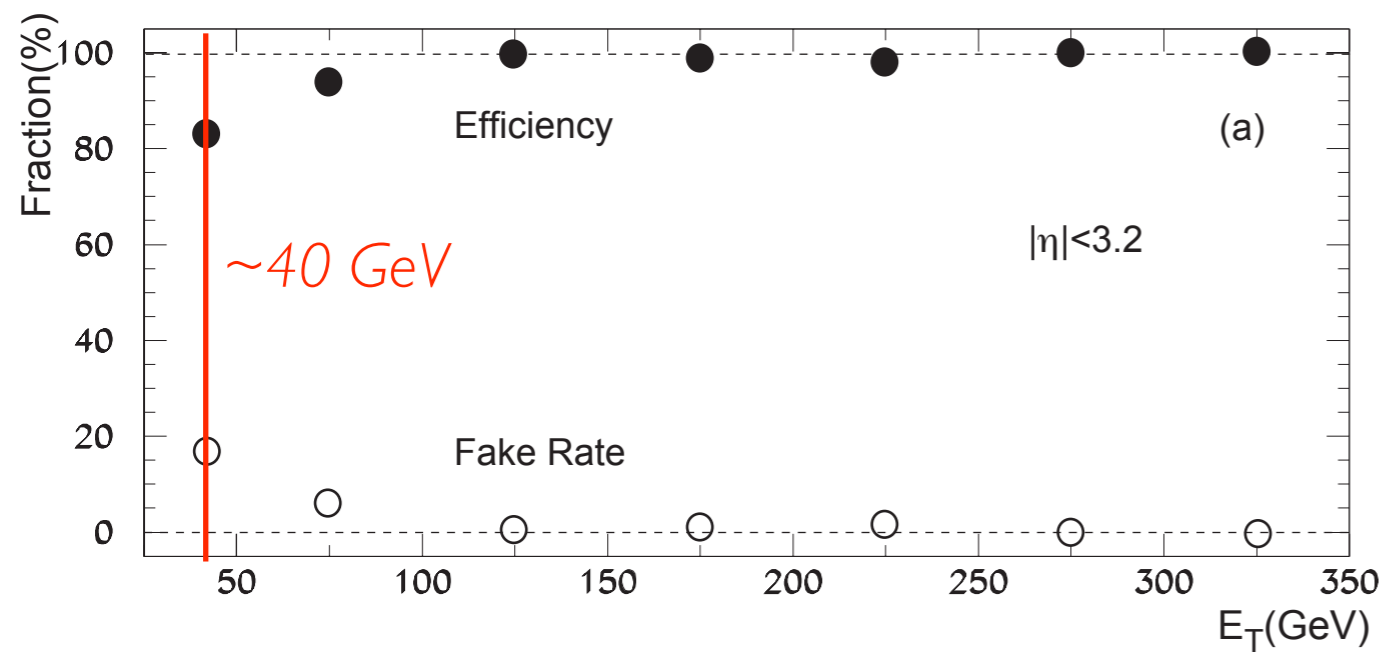
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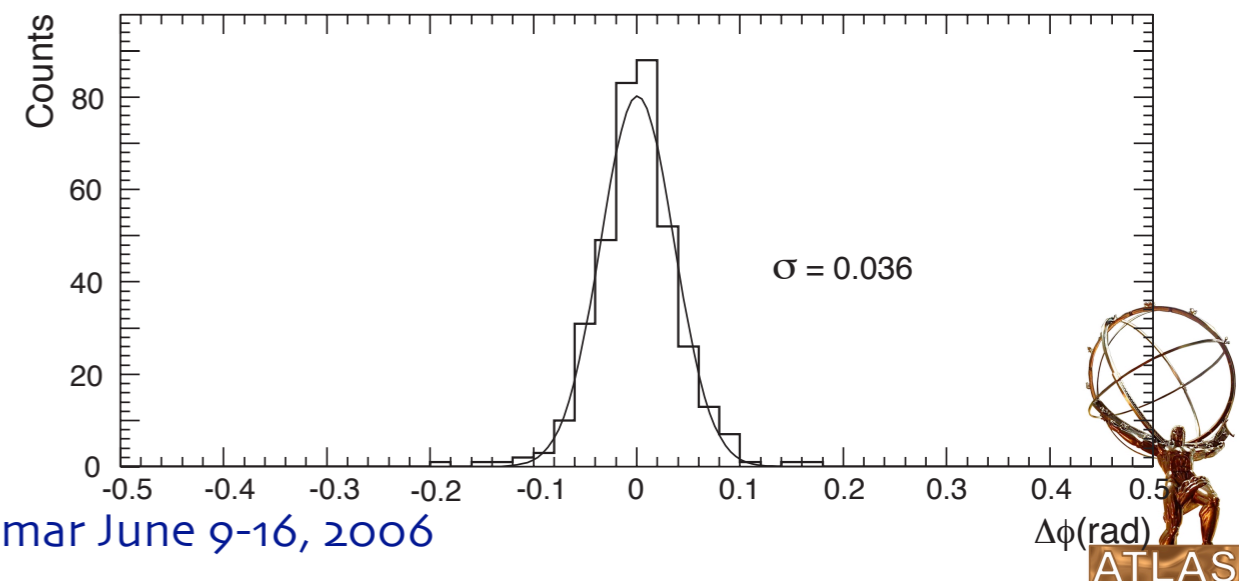
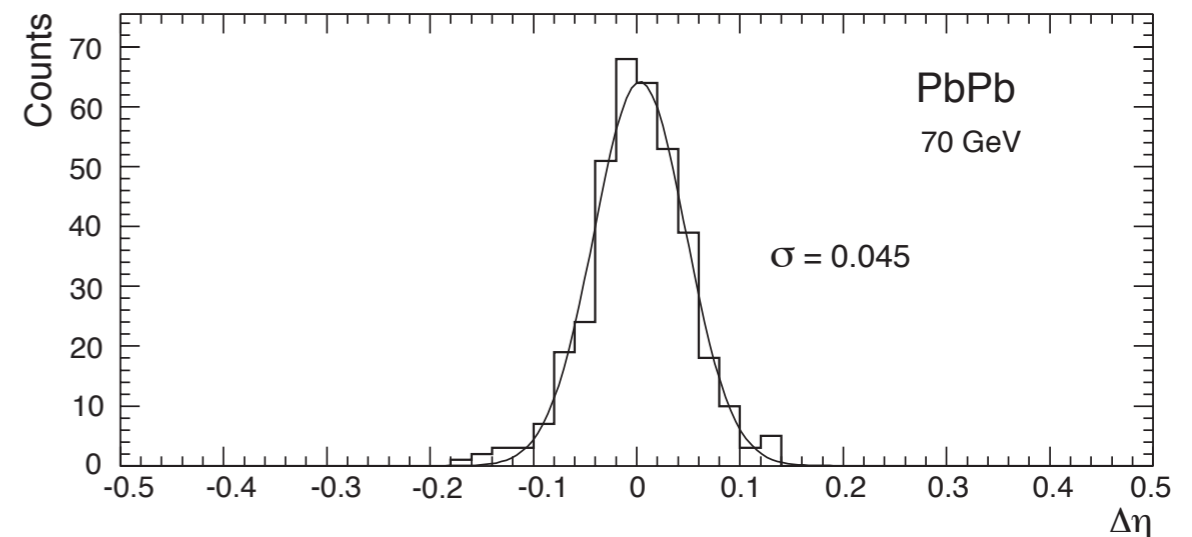
# Jet Performance

Window algorithm, with average pedestal subtraction.

Pedestal subtraction requires more study, especially if background is asymmetric.



jet axis definition is important for measurement of  $j_T$ . At the moment it is about a factor of 2 worse than pp



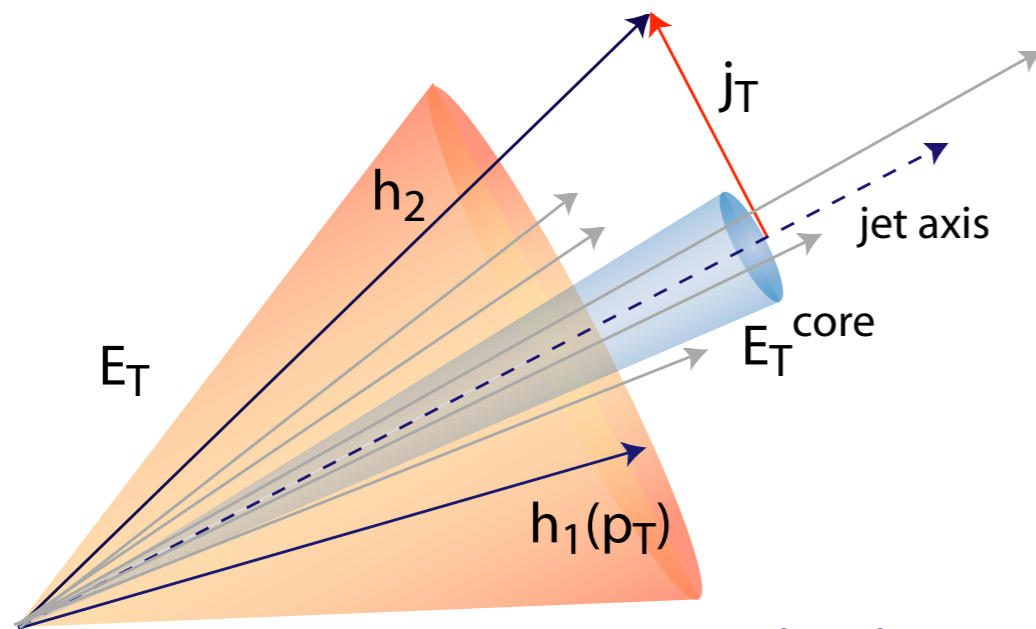
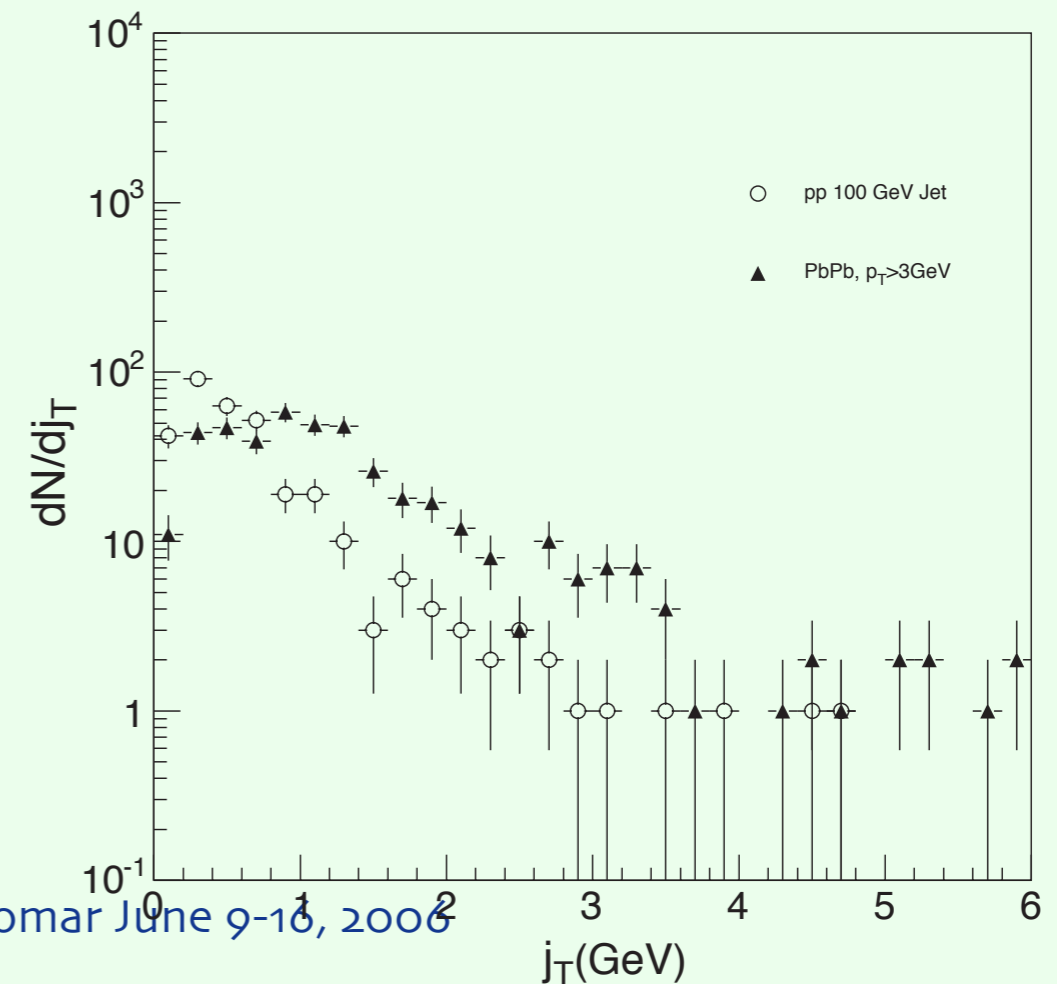
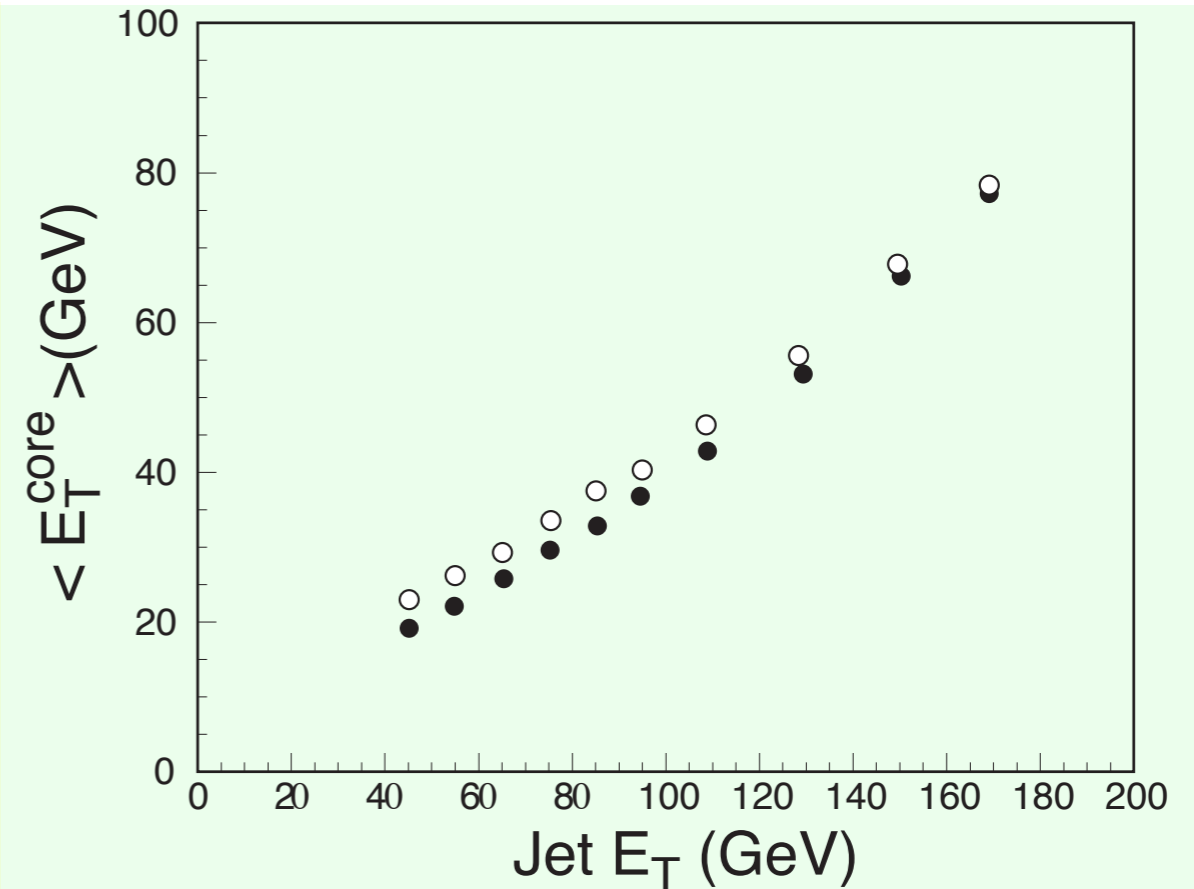
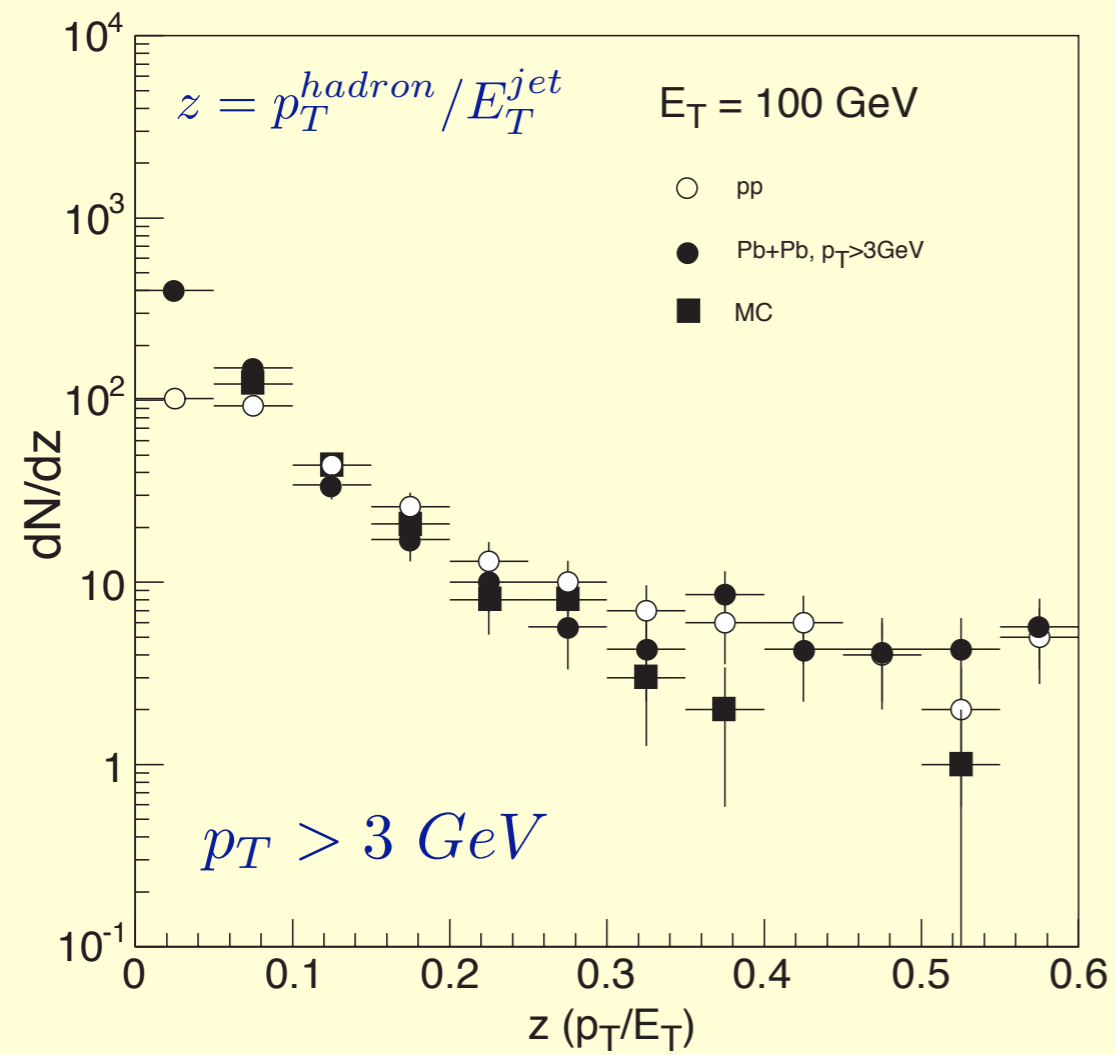
# Rates

In each  $10^6$  s run at nominal luminosity of  $4 \times 10^{26}$  we expect within  $|\eta| < 4.9$ .

Jet $E_T$ threshold	Number of events
50 GeV	$30 \times 10^6$
100 GeV	$1.5 \times 10^6$
150 GeV	$1.9 \times 10^5$
200 GeV	$4.4 \times 10^4$

We also expect  $\sim 10^6$   $\gamma$ +jet ( $E_T > 50$  GeV) events and  
 $\sim 500$   $Z^0(\mu^+\mu^-)$ +jet

# Fragmentation function, $j_T$ and $E_T^{\text{core}}$



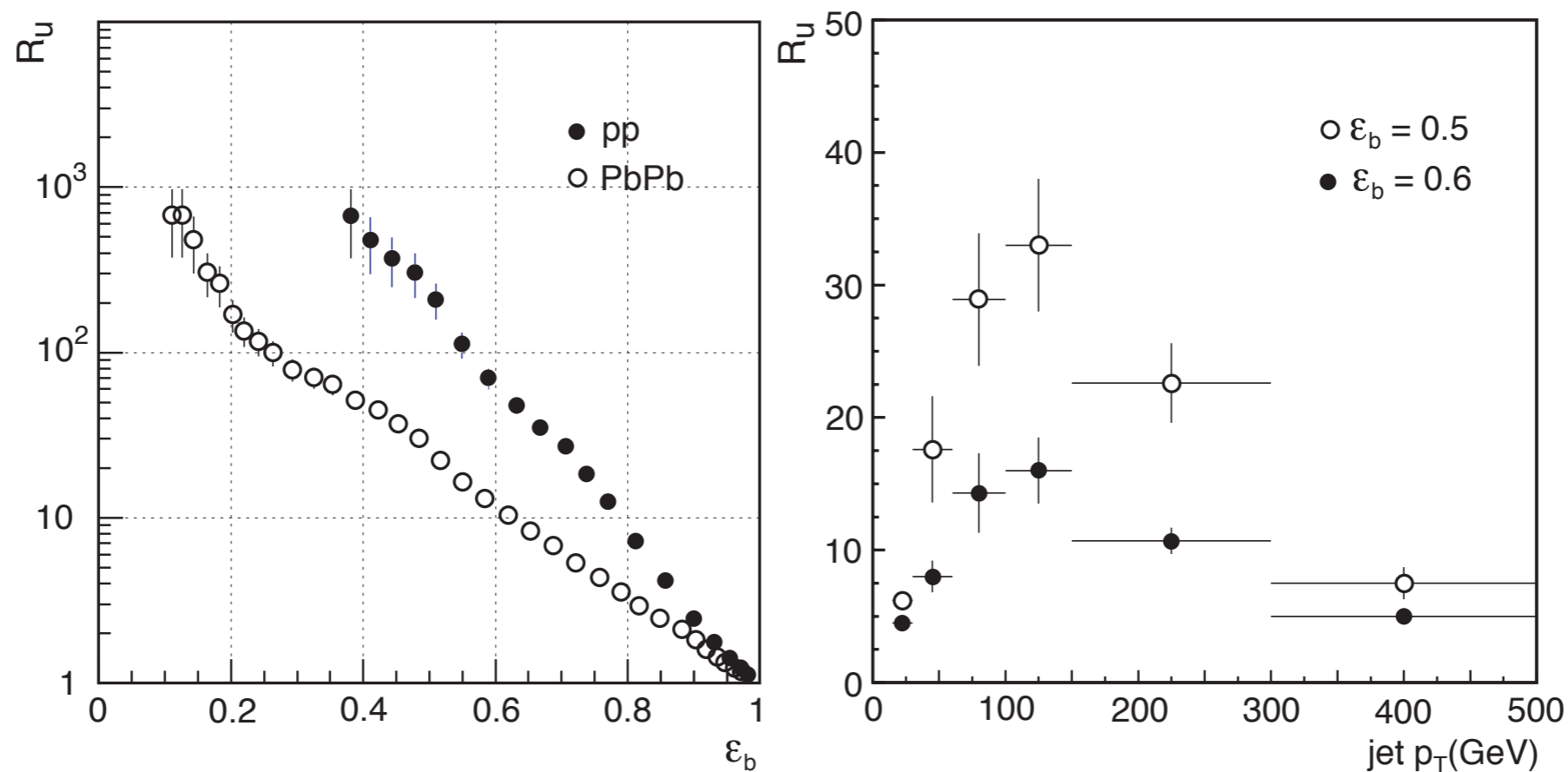
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# b- tagging

**Motivation** - Heavy quarks may radiate differently than light quarks in the hot QCD matter.

**A** first study of the  $b$ -tagging capability in the heavy ion environment was performed by overlapping WH events on HIJING background.



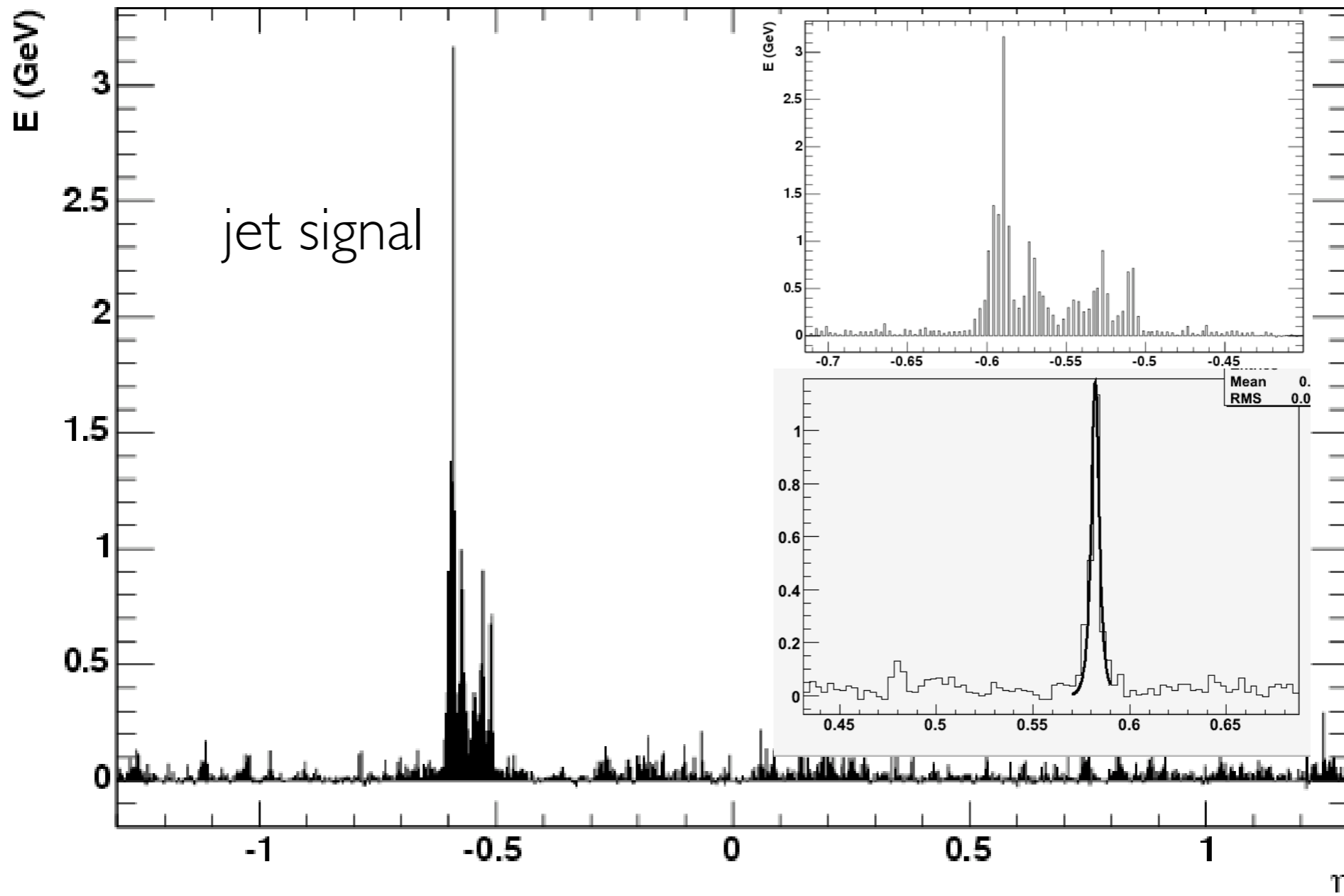
**A leptonic tag** will also be used by matching a muon in the spectrometer to the jet axis.

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# Jet Reconstruction

60% of underlying event energy is absorbed by the first calorimeter layer. Use information for jet finding and predict background in layer 2.



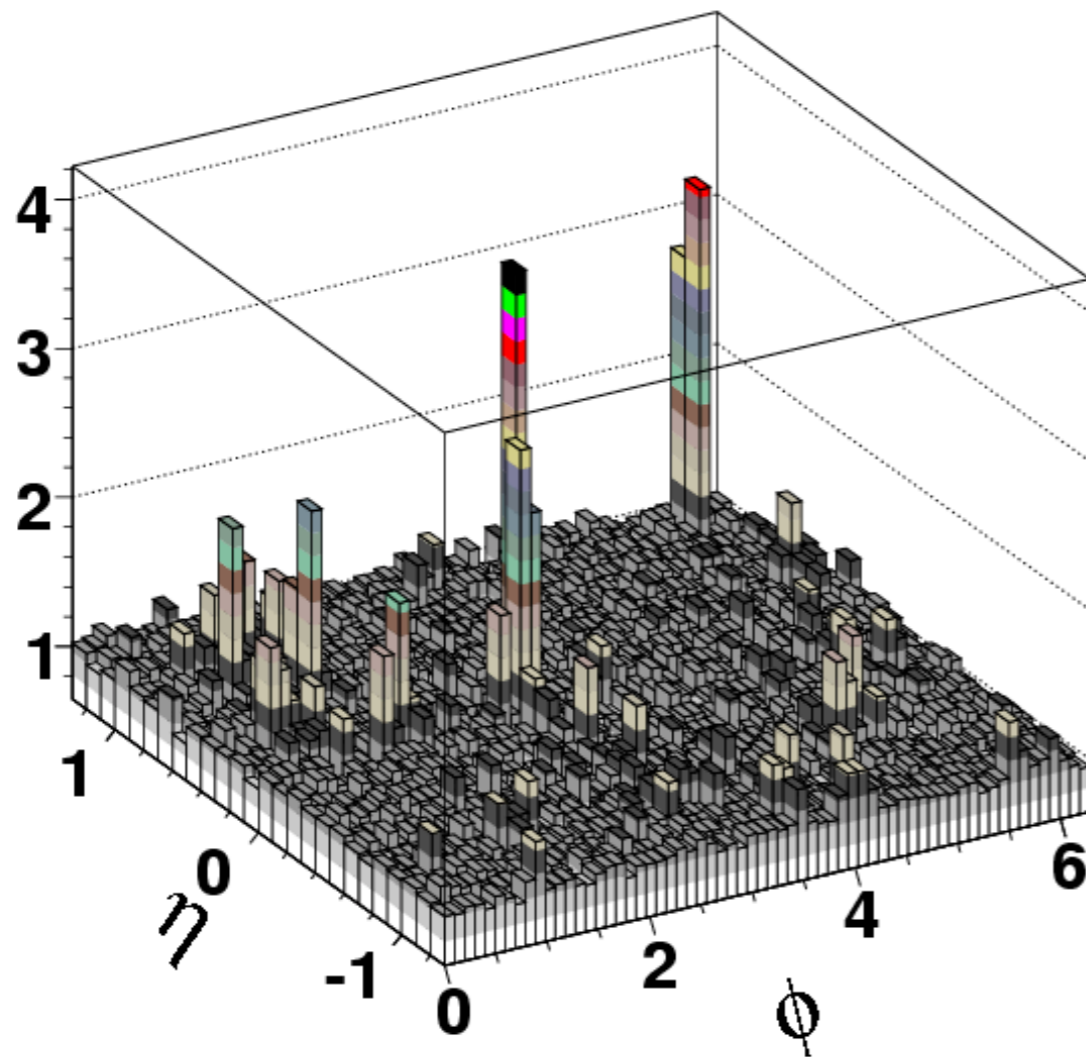
Caveat - fluctuations in photon shower, etc...

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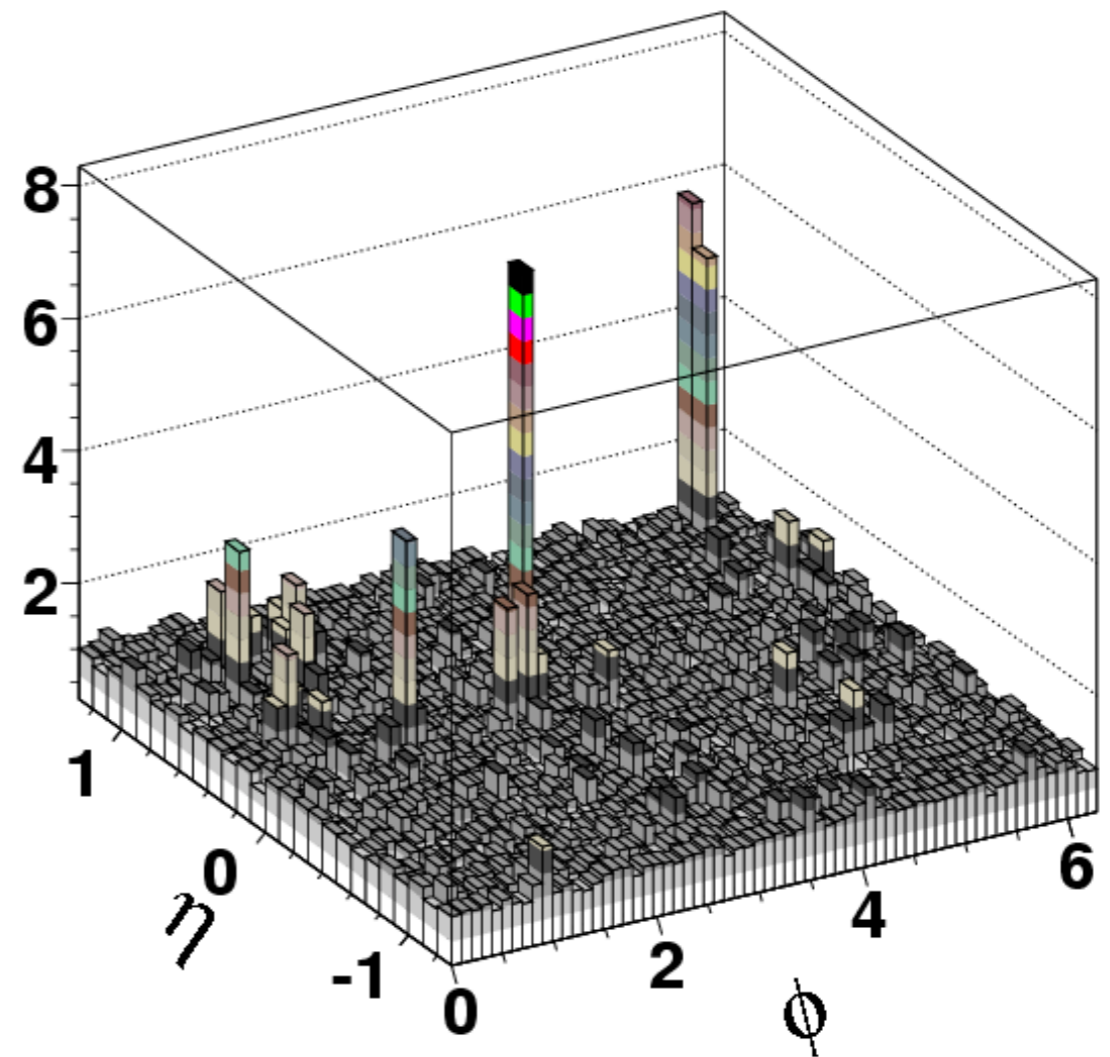


# Jet Reconstruction

Predicting the background



Jets + Underlying Event



Jets + Underlying Event  
- (predicted background)

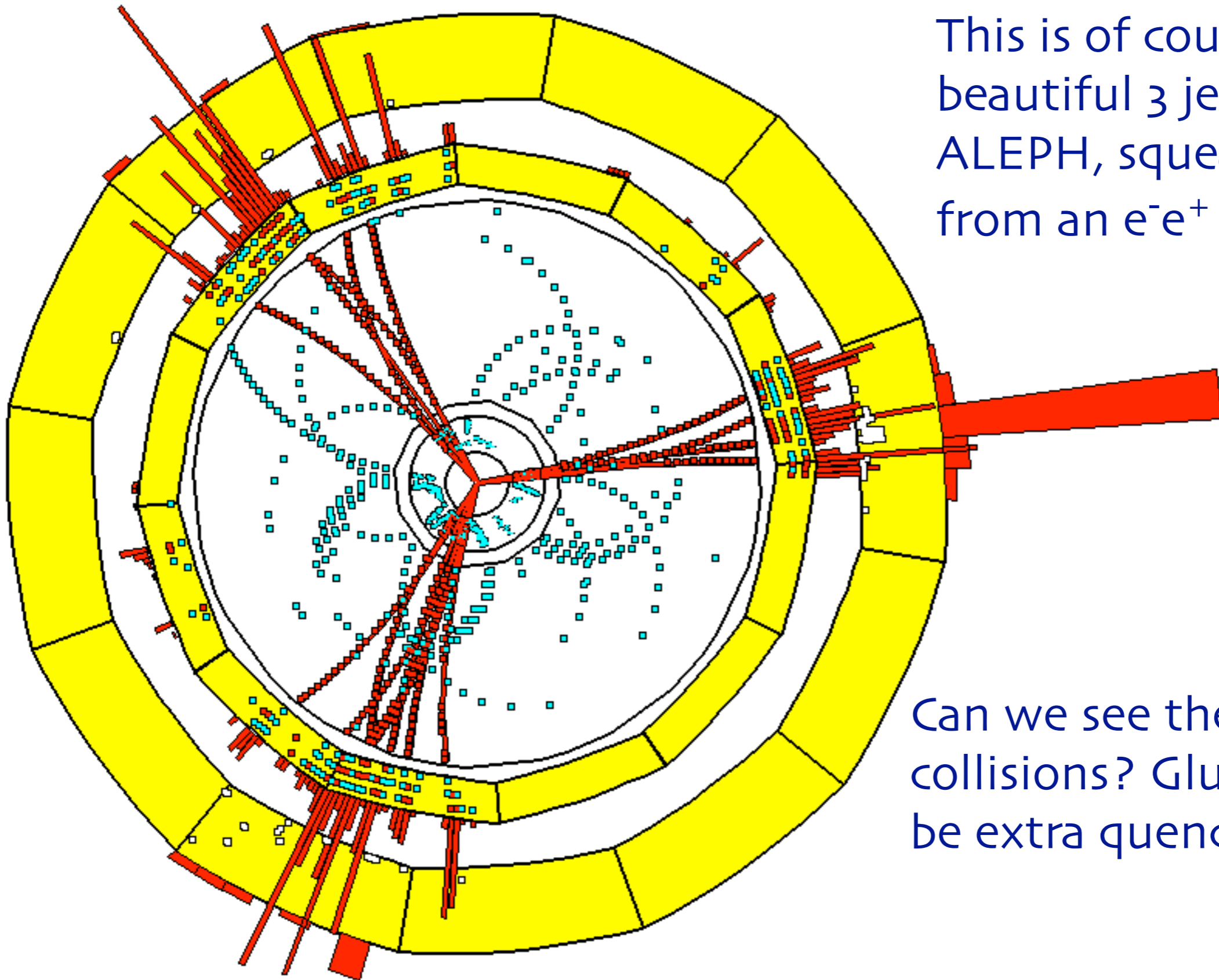
This is all very preliminary but results are very encouraging.

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# 3 jet events

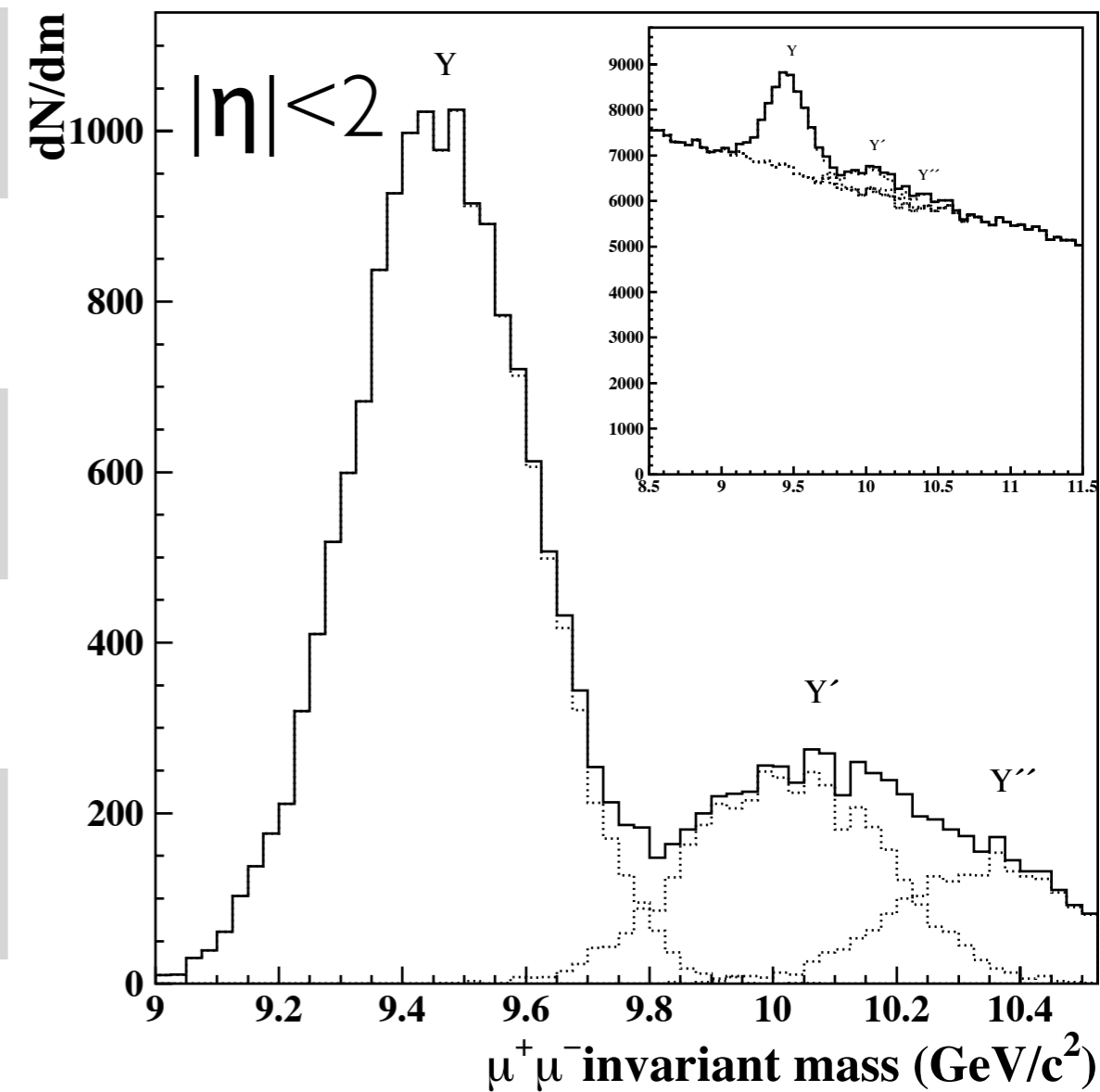
This is of course a beautiful 3 jet event from ALEPH, squeaky clean from an  $e^-e^+$  collision.



Can we see them in HI collisions? Gluon jets should be extra quenched !!

# $\Upsilon \rightarrow \mu^+ \mu^-$ Reconstruction

	$p_T(\mu) > 3 \text{ GeV}$		
	$ \eta  < 1$	$ \eta  < 2$	$ \eta  < 2.5$
Acceptance and Efficiency	2.6% 4.7%	8.1% 12.5%	12.0% 17.5%
Resolution	123 MeV	145 MeV	159 MeV
S/B	0.4 0.3	0.3 0.2	0.3 0.2
$S/(S+B)^{1/2}$	31 37	45 46	55 55
	Global Fit	Global+Tag	



For  $|\eta| < 2$  (12.5% acceptance+efficiency) we expect 15,000  $\Upsilon$  per month ( $10^6$ s) at  $\mathcal{L}=4 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$

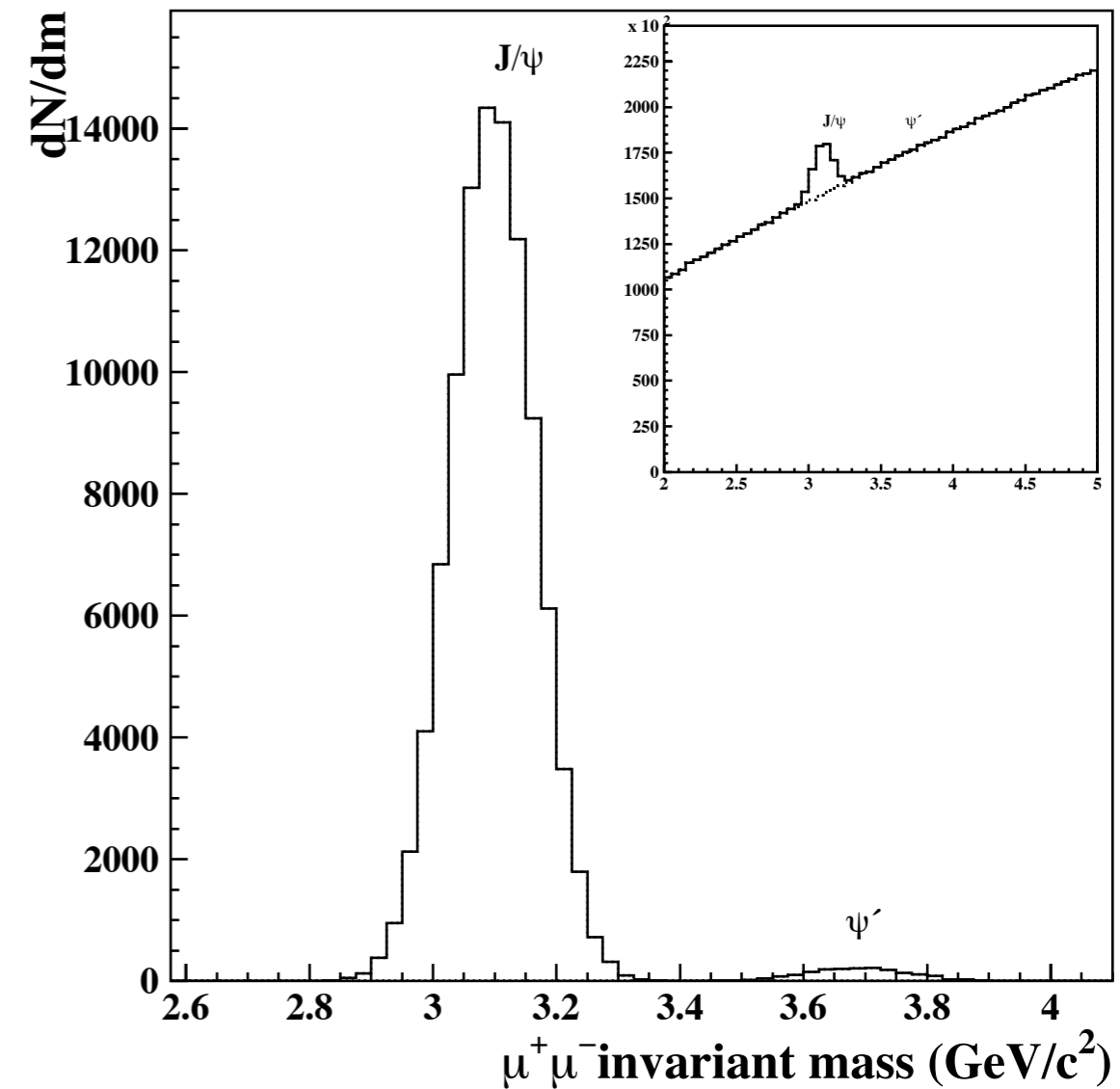
The TRT has not been considered for this study. If  $N_{ch}$  allows for its use, the mass resolution will be improved by 25%

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# $J/\Psi \rightarrow \mu^+ \mu^-$ Reconstruction

	$ \eta  < 2.5$ $p_T(\mu) > 3 \text{ GeV}$	$ \eta  < 2.5$ $p_T(\mu) > 1.5 \text{ GeV}$
Acceptance and Efficiency	<b>0.039%</b> <b>0.055%</b>	<b>0.151%</b> <b>0.530%</b>
Resolution	<b>68 MeV</b>	<b>68 MeV</b>
S/B	<b>0.5</b> <b>0.4</b>	<b>0.2</b> <b>0.15</b>
$S/(S+B)^{1/2}$	<b>52</b> <b>56</b>	<b>72</b> <b>113</b>
Rate per Month	<b>8000</b> <b>11000</b>	<b>30000</b> <b>100000</b>
	<b>Global Fit</b>	<b>Global+Tag</b>



We expect 8,000 to 100,000  $J/\psi \rightarrow \mu^+ \mu^-$  / month ( $10^6$ s) at  $\mathcal{L} = 4 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$

If a trigger is possible forward with a muon  $p_T > 1.5 \text{ GeV}$ , we gain a factor 4 in statistics. A solution might be to reduce the toroidal field for HI runs

Global+tag method increases rate by 3.5 and decreases S/B by 1.5

# The Physics Program

## High $p_T$ physics and quarkonia

Day 1 physics, multiplicity,  $dN/d\eta$ ,  $dE_T/d\eta$

Inclusive jet cross section ( $E_T > 40$  GeV)

Multi jet events (e.g. three jet events)

Heavy quarks - b-jets

“Calibrated” jets -  $\gamma+j$ ,  $Z^0+j$ ,  $\Upsilon^*+j$  and others

Measurement of jet fragmentation

“Energy Loss” vs reaction plane

Quarkonia -  $\Upsilon$  and  $J/\psi$

proton-nucleus collisions

ultra-peripheral collisions

Light ions

# Summary

ATLAS is a multi purpose detector designed for the study of high  $p_T$  physics at the LHC high luminosity environment.

The collaboration will pursue the study of heavy ion physics and the detector is especially well suited to study high  $p_T$  physics.

“Calibrated probes” will be well understood in pp studies.

Initial simulation studies indicate that the detector subsystems, trigger and data acquisition will be able to handle heavy ion events.

A major achievement has been the integration of the heavy ion group into ATLAS.

# People

K. Assamagan, M. Baker, B. Cole, R. Debbe, A. Denisov  
M. Dobbs, J. Dolejsi, F. Gianotti,  
I. Gavrilenko, N. Grau, V. Kostyukhin, J. Jia, M. Leltchouk, A.  
Lebedev, M. Levine, F. Marroquim, A. Moraes, J. Nagle, P.  
Nevski, A. Olszewski, V. Pozdnyakov, S. Timoshenko, L.  
Rosselet, M. Spousta, M. Rosati, P. Steinberg, H. Takai, S.  
Tapprogge, A. Trzupek, M.A.B. Vale, F. Videbaek, S. White, B.  
Wosiek and K. Wozniak.

Brookhaven National Laboratory  
CERN, University of Colorado  
Columbia University, Nevis Laboratories  
Iowa State  
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